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A NON-DIMENSIONAL ANALYSIS OF CARDIOVASCULAR RESPONSE TO COLD STRESS

PART II: DEVELOPMENT OF THE NON-DIMENSIONAL PARAMETERS

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CHAPTER I

Introduction and Statement of the Problem

The thermoregulatory function of the cardiovascular system is extremely complex. It involves numerous physical and chemical parameters that interact to maintain a relatively constant temperature within the body core, an anatomical region containing organs vital to the sustenance of life. Under conditions of cold, the body utilizes a variety of feedback control regulatory mechanisms that attempt both to decrease heat loss to the environment and increase heat production. The primary effector of such control is the cardiovascular system, which has the ability to rapidly change blood flow patterns throughout the body in response to this need.

The reaction of the system to a moderately cold stimulus has been studied fairly extensively and is understood quite well ~~[3,7,13].~~ Not so well understood, however, is what happens when one is subjected to extremes of cold, where body reactions can often be quite adverse. Not only is performance greatly restricted in the cold environment due to impaired musculoskeletal function, but a host of pathologic conditions result from the inability of the system to function under extremely low temperatures. In fact, the same mechanisms that attempt to protect and maintain the body in the presence of moderately cool temperatures, may indeed promote the destruction of the system when it is subjected to extremes in cold.

Relatively little is known about the physiology of temperature

regulation during prolonged periods of cold exposure. The complexities of the cardiovascular system even under normal operating conditions are vast. The fluid, blood, possesses certain non-Newtonian, anisotropic, and viscoelastic properties that directly influence its ability to transport heat. In addition to carrying heat, blood is responsible for transporting various biochemical constituents that are directly involved in thermoregulatory processes. The properties of blood are also highly temperature-dependent. For example, as the fluid is cooled it becomes more viscous and harder to pump, creating a tendency toward decreased blood flow.

An equally important constituent of cardiovascular thermoregulatory response is the vascular system, which provides the "pipes" through which the fluid is pumped. Both heat and mass transport occur across the blood vessel walls and the ease with which blood can be pumped through them is directly dependent upon various temperature-related elastic properties of the vessels themselves. In addition, the blood vessels are able to regulate the pathways of blood flow through local vasoconstrictive mechanisms in response to a cold stress.

The heart serves as the pump for the system and provides the energy needed to drive the blood. Under continuous nervous control, it can adjust its pumping rate to change cardiac output as needed.

In addition to these "hardware" components, one must also consider the intrinsic control mechanisms that govern the overall system response to any external stimulus. This would include the endocrine system as well as the central and autonomic nervous systems.

Any approach to studying the effects of cold on the cardiovascular system must necessarily account for all the governing factors mentioned above. This is to ensure model accuracy, since so many aspects of the system are interrelated and dependent on one another. The analysis must seek to isolate as many thermal, mechanical, and chemical properties of the system as possible, toward the ultimate goal of obtaining a detailed understanding of how these properties interact to protect body function effectively from temperature extremes in assaulting environments. With this in mind, the work which follows describes a non-dimensional approach which was taken to describe cardiovascular function.

Over six hundred physical and chemical variables that govern the thermoregulatory function of the cardiovascular system have been identified [13], and even this impressive list is far from exhaustive. In this study, the variables related to properties of blood, the vascular wall, the heart, and the cardiovascular control system were defined using dimensions of mass, length, time, temperature, and charge. From these, a working set of dimensionless parameters was developed using the Buckingham Pi Theorem (see Chapter III and Table 1 of Chapter IV). This allowed the thermal, mechanical, and chemical properties of the cardiovascular system to be coupled through the non-dimensionalization process. In order to obtain insight into the physics of the problem and to understand what the dimensionless groupings represent, these parameters were simplified and related to one another through geometric ratios and non-dimensional numbers common to the fields of fluid mechanics, solid and fluid heat conduction and convection, viscoelasticity, and electrochemical

diffusion (see Tables 4 and 5). On this basis, comparison of the parameters in terms of their relative significance to the problem was made. In addition, various scales were derived that are associated with electrothermodynamic processes and these were used to identify the physical significance of each parameter (see Tables 2 and 3).

Such a preliminary non-dimensional approach exploits a powerful technique for recognizing the fundamental aspects of the problem before a more complicated mathematical formulation is attempted. Because one can not initially know all the details associated with the response of the cardiovascular system to cold stress, and because there exist numerous experimental limitations that inhibit comprehensive study, a non-dimensional analysis provides a first order understanding of physical processes associated with the problem. This presents a foundation for future mathematical treatment.

In addition to identifying what experimental parameters might be useful for modeling studies, this analysis has direct application to the military, where prediction of physiologic response to adverse combat situations is often desired. Along these lines, relevant and measurable design parameters for protective clothing and gear may be proposed to enhance natural thermoregulation and compensate for adverse environmental reaction. Going one step further, the development of design parameters that may be useful in optimizing protective gear, and the suggestion of training methods to affect *conditioning or adaptation to a cold environment*, may all result from studies of this kind. By quantifying the final parameters and exploring their variability among individuals, a

basis for clinical diagnosis and treatment may be established, as well as a protocol for predicting one's susceptibility to cardiovascular stress in a cold environment.

CHAPTER II

Historical Background

The use of dimensional analysis is not recent. The development of the Buckingham Pi Theorem in 1914 provided a systematic mathematical approach to determine dimensionless groupings that contained variables pertinent to a given problem [6]. This technique is exploited in the following study and is explained in detail in Chapter III.

In 1927, Lambert and Teissier [10] first dealt with the question of circulatory similitude by proposing that the cardiac cycle and other biological periods are proportional to the length dimension of the body. Historically, similarity studies of the cardiovascular system have been based on well-established hydrodynamic principles [10]. However, such principles have often been used only to define local hemodynamic similarities without regard to the system as a whole. Current trends in this area combine such traditional methods with modern pulse transmission theory and cardiac dynamics, in an attempt to establish similarity criteria for the entire system that directly relate the physiological response of the system to its structural design [10].

A variety of cardiovascular phenomena have been explored using similarity criteria and dimensional analysis. McComis, Charm, and Kurland [11] attempted to characterize pulsating blood flow by using dimensional analysis as a method for obtaining equations which describe various pressure-velocity relationships. By investigating the parameters that

might influence the pulsating flow of blood through small tubes, and organizing these through dimensional analysis, they were successful in characterizing the steady flow of blood through small glass tubes. Further experimentation allowed the relationship between such parameters to be expressed in a simple form.

Another area where dimensional analysis has found great applicability is that of determining optimal design features of the cardiovascular system. For example, the recent works of Li and Milnor [10] have suggested that the arterial pulse transmission path length and wavelength are of such a ratio that the amount of external work performed by the ventricle at the resting heart rate is at a minimum. Using allometric equations for the given variables, a relationship may thus be derived for either ratio, and such may then be used to define a design feature of the system. Similarly, other dimensionless parameters may be used to characterize cardiac function and from these, the basis for optimal design of cardiovascular devices may be derived.

In addition to the utilization of non-dimensional analysis as it relates to design and experimentation, it has served as a means for making highly sophisticated mathematical analysis more manageable and applicable. In a study involving flows in the entrance regions of circular elastic tubes, Kuchar and Ostrach [8] made use of a non-dimensionalization scheme in order to obtain an approximate solution satisfying a simplified set of partial differential equations. Given the complexity of the equations for fluid velocity distributions, pressure distributions, and motions of the tube wall, an exact solution becomes impossible to obtain. By

introducing the non-dimensionalizing transformations for the variables involved into the Navier-Stokes equations and simplifying, significant non-dimensional fluid parameters are obtained as coefficients. These parameters contain the essential physics of the problem under investigation and, depending on their relative magnitudes, may be neglected if shown to be insignificant to the overall problem. In so doing, a simplified and more manageable set of partial differential equations is obtained which still contains the basic physics of the problem. The same technique is applied to the equations governing the motion of the tube wall. A similar non-dimensionalization scheme was used in the work of Schneck [16] to examine the phenomenon of pulsatile flow in a diverging circular channel.

Although the power of the technique is unquestionable, it has not been exploited to its fullest extent to describe the overall function of the cardiovascular system, particularly with regard to its thermoregulatory response. By reviewing the literature of past and present it becomes evident that the non-dimensional scheme is used as a tool in the simplification of equations governing specific cardiovascular phenomena only. It does not appear to be used as a method of modeling the way in which each aspect of the system interacts with one another and to what extent. It is this author's desire to explain more fully the integrated function of the cardiovascular system from the standpoint of heat and mass transport, and to do so by developing a set of dimensionless parameters that reveal the essential physics of the system without regard to complex mathematical analysis or sophisticated experimentation.

CHAPTER III

Method of Analysis

A. The Buckingham Pi Theorem

"A non-dimensional parameter or variable is any quantity, physical constant, or group of these formed in such a way that all of the units identically cancel" [16].

Such a statement is the basis for the Buckingham Pi Theorem. Developed in 1914, it provides a systematic method to develop a finite number of dimensionless parameters from a group of variables, where a fixed number of these variables are repeated in each parameter. In order to initiate such a scheme, it must first be determined which dimensions are to be considered fundamental. Most commonly, the choice for these are mass, length, and time. However, because the problem at hand is complex and involves variables representing thermal and electrical properties as well, temperature and charge must be added for a total of five fundamental dimensions. They are represented by the symbols M, L, T, θ, and q, respectively.

Once this is determined, each variable must be written in terms of the fundamental dimensions, raised to some appropriate exponential power. For example, mean arterial blood velocity would be written as L^1T^{-1}, while fluid shearing stress would be represented by $M^1L^{-1}T^{-2}$. Each of the total of k (about 600) variables defined in Reference [13] and summa-

rized in Chapter IV (Table 1) were dimensioned in such a fashion.

The next step in the non-dimensionalization scheme is to select n variables from among the total. These n variables will form the basis of the technique in the sense that they will be inherent in all the final dimensionless parameters. In this case, k is approximately equal to six hundred and $n = 5$ (representing the number of fundamental dimensions chosen). The choice for the five starting variables is essentially arbitrary except that they must contain among them all five fundamental dimensions. Since this study specifically addressed heat transport processes, this author chose variables which reflect thermal concepts related to the heat transport characteristics of blood. The variables chosen were: Thermal Conductivity of the Blood (k_t): $M^1L^1T^{-3}\theta^{-1}$, Total Thermal Capacity of the Blood (C): $M^1L^2T^{-2}\theta^{-1}$, Specific Heat of the Blood at Constant Pressure (c_p): $L^2T^{-2}\theta^{-1}$, Convection Coefficient of the Blood (film coefficient, h): $MT^{-3}\theta^{-1}$, and the Faraday Constant (F): $M^{-1}q^1$. These variables are used as "repeating variables" that can be grouped with any of the remaining variables to determine each new dimensionless parameter.

The essence of the Buckingham Pi Theorem states that, for the above-chosen variables, an equation may be written which has the form:

$$k_t{}^a C^b c_p{}^c h^d F^e (\_)^1 = M^0 L^0 T^0 \theta^0 q^0$$

The blank indicates where each of the remaining variables is to be inserted.

Rewriting each variable in terms of its own basic dimensions, the

equation becomes:

$$(M^1L^1T^{-3}\theta^{-1})^a \cdot (M^1L^2T^{-2}\theta^{-1})^b \cdot (M^0L^2T^{-2}\theta^{-1})^c \cdot (M^1L^0T^{-3}\theta^{-1})^d$$

$$(M^{-1}L^0T^0\theta^0q^1)^e \cdot (\_)^1 = M^0L^0T^0\theta^0q^0$$

By replacing the blank with each of the remaining k - n variables individually and by equating corresponding coefficients, five equations will be obtained that can be solved simultaneously for each of the five lettered exponents.

For example, in order to create the dimensionless parameter involving the electrical resistance of the vascular wall, R*, having the dimensions $M^1L^2T^{-1}\theta^0q^{-2}$, one would insert this quantity into the above equation and solve accordingly:

$$M: (1 \cdot a) + (1 \cdot b) + (0 \cdot c) + (1 \cdot d) + (-1 \cdot e) + (1) = 0$$

$$L: (1 \cdot a) + (2 \cdot b) + (2 \cdot c) + (0 \cdot d) + (0 \cdot e) + (2) = 0$$

$$T: (-3 \cdot a) + (-2 \cdot b) + (-2 \cdot c) + (-3 \cdot d) + (0 \cdot e) + (-1) = 0$$

$$\theta: (-1 \cdot a) + (-1 \cdot b) + (-1 \cdot c) + (-1 \cdot d) + (0 \cdot e) + (0) = 0$$

$$q: (0 \cdot a) + (0 \cdot b) + (0 \cdot c) + (0 \cdot d) + (1 \cdot e) + (-2) = 0$$

or

$$a + b + d - e + 1 = 0$$

$$a + 2b + 2c + 2 = 0$$

$$-3a - 2b - 2c - 3d - 1 = 0$$

$$-a - b - c - d + 0 = 0$$

$$e - 2 = 0$$

Solving these simultaneously for the exponents:

$a = -4$

$b = 2$

$c = -1$

$d = 3$

$e = 2$

Hence, the dimensionless parameter becomes:

$$k_t^{-4} C^2 c_p^{-1} h^3 F^2 R^*$$

Or:

$$\frac{C^2 h^3 F^2 R^*}{k_t^4 c_p}$$

The same technique is performed for each of the k - n remaining variables to produce k - n unique dimensionless parameters.

B. Simplification and Physical Significance of Dimensionless Parameters

Once the dimensionless parameters have been developed, it is convenient to write them in terms of some "standard" dimensionless numbers that have already been defined for specific groupings of variables. These numbers (such as the Prandtl Number, Reynolds Number, Peclet Number, and so on) are common to the fields of solid and fluid mechanics and deal with such phenomena as magneto-fluid dynamics, heat and mass transfer, viscous flow, viscoelasticity and diffusion. By isolating combinations of variables in such a manner, the physical significance of each parameter becomes more readily realized.

In order to illustrate the technique, examine the dimensionless parameter involving vascular internal diameter, D: $\frac{hD}{k_t}$, which is recognized to be the familiar Nusselt number (Nu). Physically, this represents a ratio of heat transfer by convection to heat transfer by conduction. Similarly, the dimensionless parameter involving the asymptotic limiting value of thixotropic fluid shearing stress under constant load (τ_∞): $C\tau_\infty/(k_t{}^3/c_p h)$, represents the ratio of heat generated by thixotropic shear effects to heat dissipated by a combination of convection and conduction effects. A physical significance can likewise be assigned to each of the remaining derived parameters (see Table 1).

Hence, by similar technique, a collection of parameters can be obtained which shows the types of phenomena that are prevalent to cardiovascular function. The results of this investigation are presented in Chapter IV and discussed in the sections that follow.

CHAPTER IV

Tabulated Results of the Analysis

Table 1 presents the results of a *non-dimensional analysis* of cardiovascular function and thermoregulation. It lists each variable, together with its respective symbol, dimensions, derived dimensionless parameter, and the physical significance of this parameter. The variables are grouped according to whether they are related to the blood, the heart, the vascular system, or to some overall aspect of cardiovascular function and thermoregulation.

By applying the Buckingham Pi Theorem to each variable, a unique dimensionless parameter was derived involving that variable and a combination of other thermal and electrical variables. Each derived parameter has a unique physical significance (column 5 of Table 1) that reflects the role of the cardiovascular system in thermoregulation. Through the development of these parameters, thermal, electrical, and mechanical variables are coupled together in meaningful groupings that provide a powerful insight into heat transport phenomena, without having to get involved in tedious mathematical formulations. Depending on the magnitude of the individual variables (a subject which was not specifically addressed in this work) comprising the dimensionless groupings, each parameter reflects the significance and relative importance of various electrical and thermal processes involved in thermoregulation. Derived dimensionless parameters and their corresponding physical significance are discussed in Chapter V in terms of their relationship to the blood,

heart, vascular system and overall thermoregulatory response.

In the process of non-dimensionalizing and interpreting the resulting parameters, a series of fundamental scales associated with electrothermodynamic effects was derived naturally. These results are presented in Table 2 and include scales for mass, length, time, temperature, and charge. For each of these physical quantities, a unique scale has been derived that involves the variables originally chosen as the foundation for the Buckingham Pi method of non-dimensionalization. The combinations of these variables, as shown in Table 2, represent fundamental scales for the various electrical and thermal processes that are associated with the regulation of body temperature. This is significant in that it provides the ability to derive a unique dimensionless parameter for <u>any</u> variable by simply knowing its basic dimensions. For example, the <u>Mass Density of Blood</u>, ρ_f, has the dimensions ML^{-3}. This is rewritten in terms of the derived scales:

$$(C/c_p)(k_t/h)^{-3} = Ch^3/c_p k_t{}^3$$

Hence, a unique <u>dimensionless</u> parameter is created for this variable by forming the ratio of ρ_f to this quantity: $\rho_f/(Ch^3/c_p k_t{}^3)$. This ensures a non-dimensional parameter and precludes a longer and more formal analysis that is required using the Buckingham Pi Theorem. This not only serves to simplify the task of formulating the parameter itself, but it also facilitates the analysis of what the parameter represents from a physical standpoint.

Further expanding on the concept of scales associated with electrothermodynamic processes, a series of kinematic, kinetic, thermal, and

transport quantities were written in terms of the fundamentally derived scales. These results are presented in Table 3. Having these quantities in this form simplifies the task of interpreting each derived parameter. The physical significance of many of the dimensionless parameters became evident after identifying groupings of these quantities from within the parameter itself. In this way, the translation between mathematical entity and physical phenomenon was realized.

The results of this analysis provide a valuable way to characterize cardiovascular thermoregulation through the development of a tangible set of numerical parameters consisting of several thermal and electrical variables that were selected for the purpose of the non-dimensionalization scheme. The resulting parameters may be further written in terms of more traditional dimensionless numbers, such as those listed in Table 4. These dimensionless numbers are common to the fields of solid and fluid mechanics and incorporate various heat and mass transport phenomena. Several of the dimensionless parameters derived in this study were written in terms of the traditionally defined numbers. These results are presented in Table 5. Here, variables having the same basic dimensions are grouped together for purposes of reference. A sampling of some variables, along with the resulting combination of dimensionless numbers, is provided to illustrate that the parameters derived from this study relate not only to heat and mass transport within the cardiovascular system, but they reflect even more fundamental concepts of fluid flow and heat transfer inherent within any dynamic system. Since some of the variables defined in Reference [13] are inherently dimensionless already,

there was no need to involve these variables in any further non-dimensional analysis. They should, however, be recognized as important controlling factors in the system's attempt to protect itself from temperature extremes and are indeed parameters in and of themselves. A listing of these dimensionless variables is presented in Table 6. Moreover, other variables defined in Reference [13] are difficult to quantify in the non-dimensional sense, but, either from a chemical or physical standpoint, they enhance or impede the thermoregulatory capacity of the cardiovascular system. These variables are found in Table 7 and relate to characteristics of the individual, climate, clothing, concentration and properties of carrier molecules in the blood, diet of the individual, predilection to cold stress, properties of the myocardial muscle, statistical parameters, and physical properties of the vascular system. A combination of some or all of these variables may interact to control the manner and the efficiency with which the system protects itself from an assaulting environment. To complete the list of variables, consideration must be given to the various enzymes, hormones, nutrients, vitamins, buffering ions, minerals and electrolytes, trace elements, blood gases, and byproducts of metabolism (Tables 8 - 12) that are found within the body and whose concentrations directly influence the processes of heat and mass transport.

CHAPTER V

Discussion of Results

The purpose of this work was to derive the dimensionless parameters, themselves. To actually calculate them, as well, would have been too formidable a task, and so this is left for a future study. However, some general qualitative discussion of the results obtained is in order at this point. For example, through the derivation of dimensionless parameters involving blood-related variables, various heat transfer processes are revealed that take place due to the inherent properties of blood itself. An examination of each derived parameter and its corresponding significance shows that blood has the ability to store heat, depending on its total thermal capacity, and to distribute this thermal energy throughout the body via momentum transport, molecular dispersion, ordinary diffusion, electromotive diffusion, and viscous dissipation. Each of these processes is incorporated in a respective associated Pi parameter. The variables involved are mathematically coupled with the established set of thermal and electrical variables chosen for the non-dimensionalization scheme, i.e., Thermal Conductivity of the Blood (k_t), Total Thermal Capacity of the Blood (C), Specific Heat of the Blood at Constant Pressure (c_p), Convection Coefficient of the Blood (film coefficient, h), and the Faraday Constant (F).

If one examines the derived non-dimensional parameter involving the Dynamic Elastic Modulus of Blood ($E_d(t)/(k_t/c_p)$) it is possible to interpret this ratio as the energy per volumetric flow rate of blood

associated with elastic effects, to the corresponding thermal energy (conduction) per volumetric flow rate of blood. This represents a ratio of well-defined physical quantities that relate the ability of the cardiovascular system to transport heat by each of these physical mechanisms. Similarly, the parameter involving the Dynamic Viscous Modulus of Blood ($E_j(t)/(k_t/c_p)$) represents the ratio of heat per volumetric flow rate associated with viscous dissipation in blood, to that transported by conduction. Other parameters involve the ratio of energy transported by molecular dispersion (Eddy Diffusion Coefficient, D_E), electromotive diffusion (Electromotive Diffusion Coefficient, D_s*), and ordinary diffusion (Ordinary Mass Diffusion Coefficient, D_s) to heat transported by mass and mass flux through electrothermodynamic processes. In addition to these parameters involving energy and heat transport, a ratio of heat generated per mass flow rate of blood due to viscous dissipation and heat transported per mass flow rate of blood through electrothermodynamic processes is revealed in the derived parameter involving the Kinematic Viscosity of Blood ($\nu_f/(k_t^4/Ch^3)$).

Volume ratios were also derived using other variables. The parameter involving Total Blood Volume ($V_B/(k_t^3/h^3)$ represents the ratio of total blood volume to a characteristic volume of blood associated with thermodynamic events. Similarly, other non-dimensional volume ratios were defined for variables associated with other aspects of cardiovascular thermoregulation, such as End Diastolic Volume ($EDV/(k_t^3/h^3)$), End Systolic Volume ($ESV/(k_t^3/h^3)$), and Stroke Volume ($S.V./(k_t^3/h^3)$). Each of these parameters involves the ratio of the specific heart volume

involved to the volume of blood characteristic of thermodynamic events.

Each variable in Table 1 with dimensions of time creates a unique parameter that addresses the ratio of the respective time scale associated with that particular event to the time scale associated with various thermodynamic processes. These parameters involve such time scales as the Time Spent in Core (Blood) ($t_c/(Ch/k_t^2)$) and the various ECG intervals, such as the Q-R-S Complex Interval ($t_{QRS}/(Ch/k_t^2)$). Parameters that involve frequency are merely reciprocals of time scales associated with the related phenomena. For example, the derived dimensionless parameter involving the Natural Frequency of the Vascular Wall ($\omega_n/(k_t^2/Ch)$) represents the ratio of the time scale associated with diffusion of heat through blood to the time scale associated with the kinematic translation of the vascular wall.

Variables involving pressure and stress are represented as ratios of certain energies per unit volume. The derived dimensionless parameter for Osmotic Pressure ($\pi_p/(k_t^3/Cc_ph)$), for example, represents the ratio of potential energy per unit volume associated with molecular kinetic energy driving mass across the membrane as a result of the existence of concentration gradients, to potential energy per unit volume associated with mass transport resulting from thermal gradients.

The examples presented above are not meant to be exhaustive. They merely serve to illustrate how one can interpret the physical significance represented by several types of non-dimensional parameters. Variables associated with the heart produce dimensionless parameters that reflect the role of the heart in thermoregulation. Such parameters provide a

relationship between the function of the heart-- characterized by various ECG intervals, pressures, cardiac output, cardiac volumes, heart rate; and so on-- and the electrical and thermal processes that take place within the body to control and regulate temperature. Similarly, variables related to the vascular system are found in parameters that reflect the role of the vascular system in thermal regulation. Energy per unit volume associated with elastic storage in vascular tissue, heat per unit volume associated with viscous dissipation in vascular tissue, energy transported across membranes by mass flux due to ordinary diffusion, electromotive diffusion, electromagnetic diffusion, and osmosis, and energy per unit volume associated with stress in the vascular wall are some of the quantities incorporated in the dimensionless parameters involving the vascular system.

By applying the techniques of non-dimensionalization to each variable, a dimensionless parameter is derived that relates this variable to the overall process of thermoregulation by creating a unique ratio of identifiable events. The resulting parameter provides a physical quantity to which a numerical value may be assigned. Depending on the value thus obtained, one may look, then, for a significant correlation between the function of the cardiovascular system under consideration and the mechanisms for controlling temperature within the body.

By examining the values of the derived fundamental reference scales found in Table 2 (as calculated in Reference [17]), valuable information is provided in interpreting the relative significance of various heat and mass transfer events taking place within the cardiovascular system. For

example, assuming a normal cardiac rate of 80 cycles per minute, the time scale for the transport of unsteady inertial phenomena is calculated as follows: $1/\omega = 1/2\pi f = 1/2\pi(80) = 0.002$ minutes, or, about 0.12 seconds. Similarly, calculating the time scale associated with the heat transport characteristics of blood, Ch/k_t^2, (based on values provided in Reference [17]) one obtains the following result: Ch/k_t^2 = (4.0 Kcalories/°C) (174.96 KCal/°C-hr-m^2)/(0.48 KCal/°C-hr-m)^2 = 2,975.2 hours, or about four months! The results of this simple calculation reveal that the events associated with the transport of blood through the cardiovascular system occur nearly 100 million times faster than do those associated with the ability of the fluid to dissipate heat through its own thermal properties[17]. Therefore, blood, being a poor conductor of heat, dissipates the heat generated within the body most effectively by physically carrying that heat through blood flow rather than waiting for the heat to dissipate by itself through the fluid - a process that would certainly lead to death since the body would not be able to handle the heat at the rate that it would be generated. Hence, blood can rapidly absorb and transport large quantities of heat, but it cannot easily allow that heat to move within the fluid as a result of thermal gradients associated with conductive and convective processes.

By also examining the calculated value for the reference temperature scale, 1.04×10^{-22}°C or nearly 0°C, one recognizes this as the "standard" thermodynamic reference temperature for the measurement of most heat transfer processes. The analysis thus suggests a reference temperature scale that is more generally associated with standard conditions (0°C and

atmospheric pressure) than with physiologic conditions (37°C and atmospheric pressure). Similarly, the derived length scale, k_t/h, has a calculated value of 2.75 millimeters. This is on the order of magnitude of the length of a capillary, the mean radius of a medium sized artery (or vein), or the average wall thickness of any major blood vessel, such as the aorta or the vena cava. The naturally derived mass scale, C/c_p = 4.35 kilograms, represents a mass scale associated with the heat transport characteristics of the fluid and is defined to be the total blood mass divided by the specific heat ratio of the fluid.

Therefore, as a result of this analysis, various fundamental scales associated with electrothermodynamic processes taking place within the cardiovascular system were identified and calculated. Through this process, the response of the cardiovascular system to changes in the body temperature is better understood and is able to be quantified. Such quantities may, in turn, be applied to each derived parameter to characterize its importance to overall cardiovascular thermoregulation.

Since the cardiovascular system is extremely complex, as is evident by the extensive list of variables presented in Tables 1-12, many experimental limitations are imposed upon any comprehensive study that might be undertaken. Consequently, the need arises for a more fundamental approach to determine a working set of parameters that characterize the system and, from these, to select which factors would be most significant in future modeling and experimental studies. The power of a non-dimensionalization scheme provides a method for accomplishing this task. By isolating the thermal, mechanical, and chemical variables associated

with the cardiovascular system and by developing from these a set of non-dimensional parameters, a framework is established for modeling the heat and mass transport response of the system to a given thermal input. This analysis has served to develop these working parameters and to identify the physical quantities that predict and control such a response.

CHAPTER VI

Conclusion

As a result of the non-dimensional analysis described in the preceding chapters, several significant concepts regarding cardiovascular function and thermoregulation have been developed. Using the technique of the Buckingham Pi Theorem, a dimensionless parameter was derived for each isolated variable associated with heat and mass transfer within the cardiovascular system. This parameter is unique to this variable and directly couples the related phenomenon to other thermal, mechanical, and electrical events that take place within the system.

Through the process of non-dimensionalization, a series of fundamental scales for each of the five basic dimensions was derived naturally from the resulting parameters. These were identified and quantified in Table 2. Although they may appear to be quite simplistic at first glance, they contain powerful information that permits the derivation of <u>any</u> non-dimensional parameter directly, without having to employ rigorous calculations necessitated by the Buckingham Pi Theorem. The dimensions of any selected variable can be written in terms of the derived fundamental scales. By creating a ratio of the variable to the resulting combination of fundamental scales, the non-dimensional parameter is immediately formed. The ability to create dimensionless parameters in this way is highly significant. The technique ensures that the resulting parameter is non-dimensional, and it can be performed immediately, without solving any equations beforehand. It must be reminded, however, that the simplified

method of non-dimensionalization is possible only because the fundamental scales were initially derived for the problem - a process that required the structure and methodology afforded by the Buckingham Pi Theorem.

By examining the quantitative values for the fundamental scales that resulted from this analysis (Table 2), significant information is obtained regarding heat and mass transfer within the cardiovascular system. The value obtained for the fundamental time scale, 4.16 months, appears vast when compared with the time scale for the transport of unsteady inertial phenomena - calculated to be about 0.12 seconds. This indicates that the events associated with the physical transport of blood through the cardiovascular system occur nearly 100 million times faster than do those associated with the ability of the fluid to dissipate heat through its own thermal properties. Blood is shown to be a poor conductor of heat. Hence, the human organism could not survive if it depended on blood, alone, to disperse heat due to the thermal properties of its constituents. There must be another mechanism to enhance heat transport and dissipation, and this occurs through the physical movement of the blood, or circulation. The value obtained for the fundamental time scale emphasizes that conductive heat transfer in the cardiovascular system is much smaller than that due to bulk flow.

Similarly, the other derived fundamental scales each bring a physical significance to the analysis through their respective numerical values. More important than the actual values calculated for these scales is the comparison between these values and the values associated with other events occurring within the cardiovascular system. Through such a compar-

ison, the relative significance of each event to overall cardiovascular thermoregulation is established. This type of information must be known before a more complicated analysis is attempted and, in fact, may help to develop fundamental assumptions (and simplifications) of the behavior of the cardiovascular system in its response to a thermal stress.

A non-dimensional analysis was chosen to approach this problem for the following reasons: First, the technique exploits a very powerful means for grasping the fundamental features and essential physics of any given problem before attempting to pursue a more complicated mathematical formulation. Second, it allows one to identify explicitly the important parameters that need to be measured when performing experiments that deal with physiological responses to environmental stresses. (The parameters are developed through a systematic technique and many parameters, that otherwise could only be identified through complex differential equations, are derived with relative ease using a non-dimensional scheme.) Third, criteria are established that can be used to screen individuals for their susceptibility to thermal (hot or cold) stress. Fourth, the resulting non-dimensional parameters may be used as design parameters for the development of physiologic training maneuvers and acclimatization exercises, as well as for the fabrication of thermal protection clothing and gear. And fifth, the parameters allow one to distinguish between first-order effects and higher-order effects in the analysis of data obtained from well designed thermal stress experiments.

Given the complexity of the cardiovascular system, it is necessary to develop a framework for future studies by identifying what parameters

are most significant to the analysis. Otherwise, substantial time and wasted energy may be spent to produce results that are insignificant and unrelated to the original problem. To whatever extent non-dimensional techniques may contribute to directing future research, they should be pursued in a continuing effort to improve the health, comfort, and understanding of man.

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Appendix

TABLE 1

TABULATION OF DERIVED DIMENSIONLESS PARAMETERS

A. Blood

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Activity of Solution (Effective [ ])	$\beta[S]_B$	ML^{-3}	$\dfrac{\beta[S]_B}{Ch^3/c_p k_t^3}$	Energy Per Degree Handled by the Fluid Through Conduction and Convection Associated with the Presence of Species (And Their Interactions) in Blood / Total Thermal Capacity of Blood
Asymptotic Limiting Value of Thixotropic Fluid Shearing Stress Under Constant Load	τ_∞	$ML^{-1}T^{-2}$	$\dfrac{\tau_\infty}{k_t^3/Cc_p h}$	Heat per Unit Volume Associated with Thixotropic Shear Effects / Heat per Unit Volume Dissipated by the Thermal Properties of Blood
Blood Temperature	T_B	θ	$\dfrac{T_B}{k_t^6/C^2c_p h^4}$	Blood Temperature / Reference Temperature Scale Associated with Heat Transfer Processes

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Boiling Point Temperature	T_b	θ	$\frac{T_b}{k_t^6/C^2c_ph^4}$	Boiling Point Temperature of Blood
Boiling Point Elevation of Solvent	ΔT_b			Reference Temperature Scale Associated with Heat Transfer Processes
Concentrations (See Tables 8-12)	[]	ML^{-3}	$\frac{[\ ]}{Ch^3/c_pk_t^3}$	Energy per Degree Handled by the Fluid Through Conduction and Convection Associated with the *Presence of Species in Blood*
				Total Thermal Capacity of Blood
Consistency Index of Blood	k_c	$ML^{-1}T^{(n-2)}$	$\frac{k_c}{Ch(Ch/k_t^2)^{(n-2)}/c_pk_t}$	Energy per Volumetric Flow Rate Associated with Driving Blood Through System
				Energy per Volumetric Flow Rate Associated with Thermal Properties of Fluid
Convection Conductance (Film) Coefficient	h	*	*	*

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Dynamic Elastic Modulus of Blood	$E_d(t)$	$ML^{-1}T^{-1}$	$\frac{E_d(t)}{k_t/c_p}$	Energy per Volumetric Flow Rate Associated with Elastic Storage in Blood ——— Heat per Volumetric Flow Rate Transported by Conduction
Dynamic Viscosity (Apparent Viscosity for non-Newtonian Fluid)	μ_a	$ML^{-1}T^{-1}$	$\frac{\mu_a}{k_t/c_p}$	Hydrodynamic Boundary Layer Thickness ——— Thermal Boundary Layer Thickness
Dynamic Viscous Modulus of Blood	$E_j(t)$	$ML^{-1}T^{-1}$	$\frac{E_j(t)}{k_t/c_p}$	Heat per Volumetric Flow Rate Associated with Viscous Dissipation in Blood ——— Heat per Volumetric Flow Rate Transported by Conduction
Eddy Diffusion Coefficient	D_E	L^2T^{-1}	$\frac{D_E}{k_t{}^4/Ch^3}$	Energy Transported per Mass Flow Rate of Blood by Molecular Dispersion ——— Heat Transported per Mass Flow Rate of Blood by Thermodynamic Processes

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Electromotive Diffusion Coefficient	$D_s{}^*$	$L^{-3}T_q$	$\frac{D_S{}^*}{C^2h^4F/c_pk_t{}^5}$	Charge Transported per Volumetric Flow Rate of Blood Through Electromotive Diffusion
				Charge Transported per Volumetric Flow Rate of Blood Through Electrothermodynamic Processes
Freezing Point Temperature	T_f	θ	$\frac{T_f}{k_t{}^6/C^2c_ph^4}$	Freezing Point Temperature of Blood
Freezing Point Depression of Solvent	ΔT_f			Reference Temperature Scale Associated with Heat Transfer Prosesses
Kinematic Viscosity (= μ_a/ρ_f)	ν_f	L^2T^{-1}	$\frac{\nu_f}{k_t{}^4/Ch^3}$	Heat Generated per Mass Flow Rate of Blood Due to Viscous Dissipation
				Heat Transported per Mass Flow Rate of Blood by Thermodynamic Processes
Mass Density of Blood	ρ_f	ML^{-3}	$\frac{\rho_f}{Ch^3/c_pk_t{}^3}$	Energy per Degree Handled by the Fluid through Conduction and Convection
				Total Thermal Capacity of Fluid

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Ordinary Mass Diffusion Coefficient	D_s	L^2T^{-1}	$\frac{D_s}{k_t{}^4/Ch^3}$	Energy Transported per Mass Flow Rate of Blood by Ordinary Diffusion / Heat Transported per Mass Flow Rate of Blood by Thermodynamic Processes
Osmotic Pressure	π_p	$ML^{-1}T^{-2}$	$\frac{\pi_p}{k_t{}^3/Cc_ph}$	Energy per Unit Volume Associated with Pressure Energy Driving Mass Across Membranes by Osmosis / Heat per Unit Volume of Blood Transported by Thermodynamic Processes
Quantity of Blood Pooling in Core	Q_B	L^3	$\frac{Q_B}{k_t{}^3/h^3}$	Volume of Blood Pooling in Core / Reference Volume of Blood Associated with Heat Transfer Processes
Quantity of Blood Reaching Periphery	Q_E	L^3	$\frac{Q_E}{k_t{}^3/h^3}$	Volume of Blood Reaching Periphery / Reference Volume of Blood Associated with Heat Transfer Processes

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Relaxation Time Constant of Blood	λ	T^{-1}	$\dfrac{\lambda}{k_t{}^2/Ch}$	Time Scale Associated with Diffusion of Heat Through Blood
				Time Scale Associated with Stress Relaxation
Shearing Stress	τ	$ML^{-1}T^{-2}$	$\dfrac{\tau}{k_t{}^3/Cc_ph}$	Heat per Unit Volume Generated by Fluid Shear Effects
Magnitude of Shearing Stress	$\lvert\tau\rvert$			Heat per Unit Volume Dissipated by Thermodynamic Processes
Spatial Strain Rate	$\dot{\xi}$	T^{-1}	$\dfrac{\dot{\xi}}{k_t{}^2/Ch}$	Time Scale Associated with Diffusion of Heat Through Blood
				Time Scale Associated with Spatial Strain Rate
Species Concentration in Blood	$[S]_B$	ML^{-3}	$\dfrac{[S]_B}{Ch^3/c_pk_t{}^3}$	Energy per Degree Handled by the Fluid Through Conduction and Convection Associated with the Presence of Species in Blood
				Total Thermal Capacity of Blood

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Specific Blood Volume	v_B	$M^{-1}L^3$	$\dfrac{v_B}{c_p k_t^3/Ch^3}$	Total Blood Volume per Unit Mass / Reference Volume of Blood per Unit Mass Associated with Heat Transfer Processes
Specific Heat (Constant Pressure)	c_p	*	*	*
Specific Heat (Constant Volume)	c_v	$L^2T^{-2}\theta^{-1}$	$\dfrac{c_v}{c_p}$	Heat Required to Raise 1 gram of Blood 1°C at Constant Volume / Heat Required to Raise 1 gram of Blood 1°C at Constant Pressure
Temperature of Blood at Core	T_{BC}	θ	$\dfrac{T_{BC}}{k_t^6/C^2c_ph^4}$	Temperature of Blood at Core / Reference Temperature Scale Associated with Heat Transfer Processes
Temperature of Blood at Periphery	T_{BE}	θ	$\dfrac{T_{BE}}{k_t^6/C^2c_ph^4}$	Temperature of Blood at Periphery / Reference Temperature Scale Associated with Heat Transfer Processes

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Temperature Gradient (Blood-Endothelium)	$\left(\frac{\partial T}{\partial r}\right)_w$	$L^{-1}\theta$	$\frac{\left(\frac{\partial T}{\partial r}\right)_w}{k_t^5/C^2 c_p h^3}$	"Lateral" Heat Transfer Across the Vascular Wall "Longitudinal" Heat Transfer Associated with Blood Flow
Temporal Strain Rate	$\dot{\epsilon}$	T^{-1}	$\frac{\dot{\epsilon}}{k_t^2/Ch}$	Time Scale Associated with Diffusion of Heat Through Blood Time Scale Associated with Temporal Strain Rate
Thermal Capacitance	$\rho_f c_v$	$ML^{-1}T^{-2}\theta^{-1}$	$\frac{\rho_f c_v}{Ch^3/k_t^3}$	Total Thermal Capacity of Total Blood Volume Total Thermal Capacity of Blood Volume Involved in Conductive and Convective Heat Transfer
Thermal Conductivity	k_t	*	*	*

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Thermal Diffusivity	α	L^2T^{-1}	$\dfrac{\alpha}{k_t{}^4/Ch^3}$	Time Rate of Change of Temperature in Blood / Time Rate of Heat Influx or Efflux from Blood
Time-Dependent Shearing Stress	$\tau(t)$	$ML^{-1}T^{-2}$	$\dfrac{\tau(t)}{k_t{}^3/Cc_ph}$	Heat per Unit Volume Generated by Fluid Shear Effects Over Time / Heat per Unit Volume Dissipated Over Time by Thermodynamic Processes
Time Spent in Core (Blood)	t_c	T	$\dfrac{t_c}{Ch/k_t{}^2}$	Time Scale Associated with Blood in Core / Time Scale Associated with Diffusion of Heat Through Blood
Time Spent in Periphery (Blood)	t_a	T	$\dfrac{t_a}{Ch/k_t{}^2}$	Time Scale Associated with Blood at Periphery / Time Scale Associated with Diffusion of Heat Through Blood

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Total Blood Volume	V_B	L^3	$\frac{V_B}{k_t{}^3/h^3}$	Total Blood Volume / Reference Volume of Blood Associated with Heat Transfer Processes
Total Thermal Capacity	C	*	*	*
Velocity Gradient of Blood at Wall	$(\frac{\partial v}{\partial r})_w$	T^{-1}	$\frac{(\frac{\partial v}{\partial r})_w}{k_t{}^2/Ch}$	Change in Velocity of Blood with Respect to Radial Distance at the Wall Due to Viscous Shear Effects / Change in Velocity of Blood per Unit Length Traversed Due to Thermodynamic Effects
Viscoelastic Complex Modulus Magnitude of Viscoelastic Complex Modulus	$E_r(t)$ $\lvert E_r(t)\rvert$	$ML^{-1}T^{-1}$	$\frac{E_r(t)}{k_t/C_p}$	Energy per Volumetric Flow Rate Associated with Elastic Storage and Viscous Dissipation in Blood / Heat per Volumetric Flow Rate Transported by Conduction

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Yield Stress	τ_y	$ML^{-1}T^{-2}$	$\dfrac{\tau_y}{k_t^3/Cc_p h}$	$\dfrac{\text{Heat per Unit Volume Associated with Fluid Yield Stress}}{\text{Heat per Unit Volume Dissipated by Thermodynamic Processes}}$

TABLE 1 (continued)

B. HEART

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Amplitude of Ventricular Pressure	Δp_v	$ML^{-1}T^{-2}$	$\dfrac{\Delta p_v}{k_t{}^3/Cc_p h}$	Energy per Unit Volume Associated with Pressure Energy (Potential) in Heart
				Heat per Unit Volume of Blood Transported by Thermodynamic Processes
Circular Frequency of Oscillating Blood Flow (= $2\pi f$)	ω	T^{-1}	$\dfrac{\omega}{k_t{}^2/Ch}$	Time Scale Associated with Diffusion of Heat Through Blood
				Time Scale Associated with Kinematic Translation of Blood Through the Cardiovascular System
Conduction Velocity Through Myocardial Musculature	u	LT^{-1}	$\dfrac{u}{k_t{}^3/Ch^2}$	Rate of Conduction Through Myocardial Musculature
				Rate at which Heat Diffuses Through Blood

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Coronary Perfusion Rate	Q_c	L^3T^{-1}	$\frac{Q_c}{k_t^5/Ch^4}$	Volume of Blood per Unit Time Perfusing the Heart
				Reference Volume of Blood per Unit Time Associated with Heat Transfer Processes
ECG Intervals "Corrected" Q-T Duration (same as S-T Segment Interval)	t_{QT}'	T	$\frac{t_{QT}'}{Ch/k_t^2}$	Time Scale Associated with Completion of Ventricular Depolarization and Beginning of Ventricular Repolarization
				Time Scale Associated with Diffusion of Heat Through Blood
P-Wave Interval	t_P	T	$\frac{t_P}{Ch/k_t^2}$	Time Scale Associated with Atrial Depolarization
				Time Scale Associated with Diffusion of Heat Through Blood
P-Q Wave Interval	t_{PQ}	T	$\frac{t_{PQ}}{Ch/k_t^2}$	Time Scale Associated with Atrial Depolarization and Propagation of Sino-Atrial Signal
				Time Scale Associated with Diffusion of Heat Through Blood

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
P-R Segment Interval	$t_{PR}*$	T	$\frac{t_{PR}*}{Ch/k_t^2}$	Time Scale Associated with Atrio-Ventricular Node Delay
				Time Scale Associated with Diffusion of Heat Through Blood
P-R Wave Interval	t_{PR}	T	$\frac{t_{PR}}{Ch/k_t^2}$	Time Scale Associated with Atrio-Ventricular Conduction
				Time Scale Associated with Diffusion of Heat Through Blood
Pre-Ejection Period (= $t_{VS}-t_V$)	t_{SE}	T	$\frac{t_{SE}}{Ch/k_t^2}$	Time Scale Associated with Pre-Ejection Period
				Time Scale Associated with Diffusion of Heat Through Blood
P-U Wave Interval (= t_{RR} = t_{PP})	t_{PU}	T	$\frac{t_{PU}}{Ch/k_t^2}$	Time Scale Associated with P-U Wave Interval
				Time Scale Associated with Diffusion of Heat Through Blood

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Q-Wave Interval	t_Q	T	$\frac{t_Q}{Ch/k_t}$	Time Scale Associated with Propagation of the Sino-Atrial Signal Through the Interventricular Septum
				Time Scale Associated with Diffusion of Heat Through Blood
Q-R-S Complex Interval (same as Q-S Wave Interval)	t_{QRS}	T	$\frac{t_{QRS}}{Ch/k_t}$	Time Scale Associated with Ventricular Depolarization
				Time Scale Associated with Diffusion of Heat Through Blood
Q-T Duration: "Electrical Systole"	t_{QT}	T	$\frac{t_{QT}}{Ch/k_t}$	Time Scale Associated with "Electrical Systole"
				Time Scale Associated with Diffusion of Heat Through Blood
R-Wave Interval	t_R	T	$\frac{t_R}{Ch/k_t}$	Time Scale Associated with the Propagation of Sino-Atrial Signal Through Right Ventricular Musculature
				Time Scale Associated with Diffusion of Heat Through Blood

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
R'-Wave Interval	$t_{R'}$	T	$\frac{t_{R'}}{Ch/k_t}$	Time Scale Associated with R' Wave Interval Time Scale Associated with Diffusion of Heat Through Blood
Refractory Time of Cardiac Muscle	t_r	T	$\frac{t_r}{Ch/k_t}$	Refractory Time of Cardiac Muscle Time Scale Associated with Diffusion of Heat Through Blood
R-R Wave Interval (Cardiac Period = 1/f)	t_{RR}	T	$\frac{t_{RR}}{Ch/k_t}$	Time Scale Associated with the Kinematic Translation of Blood Through the Cardiovascular System (Cardiac Period) Time Scale Associated with Diffusion of Heat Through Blood
S-Wave Interval	t_S	T	$\frac{t_S}{Ch/k_t}$	Time Scale Associated with Completion of Ventricular Depolarization Time Scale Associated with Diffusion of Heat Through Blood

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Sino-Atrial Node Period	t_{SA}	T	$\frac{t_{SA}}{Ch/k_t^2}$	Sino-Atrial Node Period / Time Scale Associated with Diffusion of Heat Through Blood
S-T Wave Interval	t_{ST}	T	$\frac{t_{ST}}{Ch/k_t^2}$	Time Scale Associated with Completion of Ventricular Depolarization and Beginning of Ventricular Repolarization / Time Scale Associated with Diffusion of Heat Through Blood
T-Wave Interval	t_T	T	$\frac{t_T}{Ch/k_t^2}$	Time Scale Associated with Ventricular Repolarization / Time Scale Associated with Diffusion of Heat Through Blood
Time to Closure of Aortic Valve	t_{S_2}	T	$\frac{t_{S_2}}{Ch/k_t^2}$	Time to Closure of Aortic Valve / Time Scale Associated with Diffusion of Heat Through Blood

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Time to Onset of QRS Complex (AV Node Delay)	t_{AV}	T	$\frac{t_{AV}}{Ch/k_t^2}$	Atrio-Ventricular Node Delay Time Scale Associated with Diffusion of Heat Through Blood
U-Wave Interval	t_U	T	$\frac{t_U}{Ch/k_t^2}$	Time Scale Associated with Membrane After Potentials Time Scale Associated with Diffusion of Heat Through Blood
Ventricular Diastole	t_d	T	$\frac{t_d}{Ch/k_t^2}$	Time Scale Associated with Ventricular Diastole Time Scale Associated with Diffusion of Heat Through Blood
Ventricular Electromechanical Systole (= $t_{S_2} - t_{AV}$)	t_{VS}	T	$\frac{t_{VS}}{Ch/k_t^2}$	Time Scale Associated with Ventricular Electromechanical Systole Time Scale Associated with Diffusion of Heat Through Blood

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Ventricular Systole = Left Ventricular Ejection Time ($=t_D - t_0$)	t_V	T	$\frac{t_V}{Ch/k_t^2}$	Left Ventricular Ejection Time / Time Scale Associated with Diffusion of Heat Through Blood
End Diastolic Volume	EDV	L^3	$\frac{EDV}{k_t^3/h^3}$	End Diastolic Volume of Blood / Reference Volume of Blood Associated with Heat Transfer Processes
End Systolic Volume	ESV	L^3	$\frac{ESV}{k_t^3/h^3}$	End Systolic Volume of Blood / Reference Volume of Blood Associated with Heat Transfer Processes
Firing Frequency of *Cardiac Mechanoreceptors*	f_{CM}	T^{-1}	$\frac{f_{CM}}{k_t^2/Ch}$	Time Scale Associated with Diffusion *of Heat Through Blood* / Time Scale Associated with the Firing Rate of Cardiac Mechanoreceptors
Intrinsic "Natural Frequency" of Sino-Atrial Node	f_{SA}	T^{-1}	$\frac{f_{SA}}{k_t^2/Ch}$	Time Scale Associated with Diffusion of Heat Through Blood / Time Scale Associated with Intrinsic "Natural Frequency" of the Sino-Atrial Node

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Left Ventricular Compliance	$\frac{dp}{dV}$	$ML^{-4}T^{-2}$	$\dfrac{\frac{dp}{dV}}{h^2/Cc_p}$	Change in Elastic Energy per Unit Volume of Tissue per Unit Volume of Blood Stored in the Left Ventricle of the Heart ——— Change in Heat per Unit Volume of Blood per Length of Blood Vessel Traversed per Area Available for Heat Transfer
Mass of Heart	m_H	M	$\dfrac{m_H}{C/c_p}$	Mass of Heart ——— Mass Scale Associated with Heat Transfer Processes
Maximum Velocity of Contractile Element Shortening	v_m	LT^{-1}	$\dfrac{v_m}{k_t{}^3/Ch^2}$	Maximum Velocity of Contractile Element Shortening ——— Rate at Which Heat Diffuses Through Blood
Maximum Ventricular Blood Pressure	$p_{vmaxsys}$	$ML^{-1}T^{-2}$	$\dfrac{p_{vmaxsys}}{k_t{}^3/Cc_ph}$	Energy per Unit Volume Associated with Pressure Energy (Potential) in Heart During Systole ——— Heat per Unit Volume of Blood Transported by Thermodynamic Processes

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Mean Left Ventricular Blood Pressure (Aorta) = 1/2($P_{systolic}$ + $P_{diastolic}$)	P_{ao}	$ML^{-1}T^{-2}$	$\frac{P_{ao}}{k_t{}^3/Cc_ph}$	Energy per Unit Volume Associated with Mean Pressure Energy (Potential) in Aorta ——— Heat per Unit Volume of Blood Transported by Thermodynamic Processes
Minimum Diastolic Blood Pressure (Arterial)	P_{diamin}	$ML^{-1}T^{-2}$	$\frac{P_{diamin}}{k_t{}^3/Cc_ph}$	Energy per Unit Volume Associated with Minimum Arterial Pressure Energy (Potential) During Diastole ——— Heat per Unit Volume of Blood Transported by Thermodynamic Processes
Minimum Ventricular Blood Pressure	$P_{vmindia}$	$ML^{-1}T^{-2}$	$\frac{P_{vmindia}}{k_t{}^3/Cc_ph}$	Energy per Unit Volume Associated with Pressure Energy (Potential) in Heart During Diastole ——— Heat per Unit Volume of Blood Transported by Thermodynamic Processes
Myocardial Contraction Velocity	u_m	LT^{-1}	$\frac{u_m}{k_t{}^3/Ch^2}$	Myocardial Contraction Velocity ——— Rate at which Heat Diffuses Through Blood

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Parasympathetic Firing Rate	f_p	T^{-1}	$\frac{f_p}{k_t^2/Ch}$	Time Scale Associated with Diffusion of Heat Through Blood ——— Time Scale Associated with Parasympathetic Firing Rate
Peak Systolic Blood Pressure (Arterial)	p_{sysmax}	$ML^{-1}T^{-2}$	$\frac{p_{sysmax}}{k_t^3/Cc_ph}$	Energy per Unit Volume Associated with Maximum Arterial Pressure Energy (Potential) During Systole ——— Heat per Unit Volume of Blood Transported by Thermodynamic Processes
Power Input	Φ_H	ML^2T^{-3}	$\frac{\Phi_H}{k_t^8/C^2c_ph^5}$	Rate at which Potential Energy is Imparted to Blood ——— Rate of Heat Diffusion Through Blood
Power Output (= $\Phi_H \cdot n_t$)	Φ_{OH}	ML^2T^{-3}	$\frac{\Phi_{OH}}{k_t^8/C^2c_ph^5}$	Rate at Which Kinetic Energy is Imparted to Blood ——— Rate of Heat Diffusion Through Blood

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Pulse Pressure (= $P_{systolic} - P_{diastolic}$)	P_p	$ML^{-1}T^{-2}$	$\frac{P_p}{k_t^3/Cc_ph}$	Energy per Unit Volume Associated with Pressure Energy (Potential) Driving Blood Flow Heat per Unit Volume of Blood Transported by Thermodynamic Processes
Pulse Rate (Linear Frequency of Oscillating Blood Flow)	f	T^{-1}	$\frac{f}{k_t^2/Ch}$	Time Scale Associated with Diffusion of Heat Through Blood Time Scale Associated with Kinematic Translation of Blood Through the Cardiovascular System
Rate of Change of Ventricular Pressure with Time (Carotid Artery)	$\frac{dp}{dt}$	$ML^{-1}T^{-3}$	$\frac{\frac{dp}{dt}}{k_t^5/C^2c_ph^2}$	Rate of Change of Ventricular Pressure with Time Rate of Change of Heat per Unit Blood Volume per Unit Time Associated with Heat Transfer Processes
Rate of O_2 Consumption (Myocardial Muscle)	$\dot{V}_{mO_2}$	L^3T^{-1}	$\frac{\dot{V}_{mO_2}}{k_t^5/Ch^4}$	Volume of O_2 per Unit Time Consumed by Myocardial Muscle Volume of Blood per Unit Time Involved in Heat Transfer

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Right Atrial Blood Pressure	p_{ra}	$ML^{-1}T^{-2}$	$\frac{p_{ra}}{k_t{}^3/Cc_p h}$	Energy per Unit Volume Associated with Pressure Energy (Potential) in Right Atrium of Heart ——— Heat per Unit Volume Transported by Thermodynamic Processes
Stroke Power	Φ	ML^2T^{-3}	$\frac{\Phi}{k_t{}^8/C^2c_p h^5}$	Rate at Which Kinetic Energy is Imparted to Blood During Systole ——— Rate of Heat Diffusion Through Blood
Stroke Volume	S.V.	L^3	$\frac{S.V.}{k_t{}^3/h^3}$	Stroke Volume of Blood ——— Reference Volume of Blood Associated with Heat Transfer Processes
Sympathetic Firing Rate	f_S	T^{-1}	$\frac{f_S}{k_t{}^2/Ch}$	Time Scale Associated with Diffusion of Heat Through Blood ——— Time Scale Associated with Sympathetic Firing Rate

TABLE 1 (*continued*)

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Threshold Pressure (to fire receptor)	p_t	$ML^{-1}T^{-2}$	$\frac{p_t}{k_t{}^3/Cc_ph}$	Energy per Unit Volume Associated with Pressure Energy (Potential) Needed to Fire Receptor / Heat per Unit Volume of Blood Transported by Thermodynamic Processes
Time to Beginning of Pressure Upstroke	t_o	T	$\frac{t_o}{Ch/k_t{}^2}$	Time to Beginning of Pressure Upstroke / Time Scale Associated with Diffusion of Heat Through Blood
Time to Dicrotic Notch on Pressure Curve	t_D	T	$\frac{t_D}{Ch/k_t{}^2}$	Time to Dicrotic Notch on Pressure Curve / Time Scale Associated with Diffusion of Heat Through Blood
Total Cardiac Output	C.O.	L^3T^{-1}	$\frac{C.O.}{k_t{}^5/Ch^4}$	Total Cardiac Output / Reference Volume of Blood per Unit Time Associated with Heat Transfer Processes

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Total Peripheral Resistance	R_T	$ML^{-4}T^{-1}$	$\frac{R_T}{h^3/c_p k_t^2}$	Energy per Volumetric Flow Rate of Blood per Unit Volume of Vascular Tissue Associated with the Resistance to Blood Flow
				Energy per Volumetric Flow Rate of Blood per Volume of Blood Vessel Traversed Associated with Thermodynamic Properties of Fluid
Venous Return to Right Atrium of Heart	Q_{RA}	L^3T^{-1}	$\frac{Q_{RA}}{k_t^5/Ch^4}$	Volume of Blood per Unit Time Returned to Right Atrium of Heart
				Reference Volume of Blood per Unit Time Associated with Heat Transfer Processes

Table 1 (continued)

C. VASCULAR SYSTEM

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Acceleration of Blood Leaving Ventricles	a_B	LT^{-2}	$\frac{a_B}{k_t^5/C^2h^3}$	Acceleration of Blood Leaving Ventricles Heat per Unit Mass Transported Over a Given Length of Blood Vessel Through Thermodynamic Processes
Active Transport Permeability Coefficient	P_A	LT^{-1}	$\frac{P_A}{k_t^3/Ch^2}$	Rate at Which Mass is Transported by Active Transport Through Membranes Rate at Which Heat Diffuses Through Blood
Arrangement of Roughness Elements (Spacing)	ζ^*	L	$\frac{\zeta^*}{k_t/h}$	Length Scale Associated with Arrangement of Roughness Elements on Vascular Tissue Length Scale Associated with Heat Transfer Processes
Arterial Blood Pressure	$p(t)$	$ML^{-1}T^{-2}$	$\frac{p(t)}{k_t^3/Cc_ph}$	Energy per Unit Volume Associated with Arterial Pressure Energy (Potential) Over Time Heat per Unit Volume of Blood Transported by Thermodynamic Processes

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Arterial Partial Pressure of O_2	pO_2	$ML^{-1}T^{-2}$	$\dfrac{pO_2}{k_t^3/Cc_ph}$	Energy per Unit Volume Associated with Arterial Partial Pressure of O_2 / Heat per Unit Volume of Blood Transported by Thermodynamic Processes
Central Venous Pressure	P_{cv}	$ML^{-1}T^{-2}$	$\dfrac{P_{cv}}{k_t^3/Cc_ph}$	Energy per Unit Volume Associated with Venous Pressure Energy (Potential) / Heat per Unit Volume of Blood Transported by Thermodynamic Processes
Complex Compliance:	$\bar{J}$	$M^{-1}LT^2$	$\dfrac{\bar{J}}{Cc_ph/k_t^3}$	Heat per Unit Volume of Blood Transported by Thermodynamic Processes / Energy per Unit Volume Associated with Elastic Storage and Viscous Dissipation in Vascular Tissue
Storage Compliance	$\bar{J}_r(\omega)$	$M^{-1}LT^2$	$\dfrac{\bar{J}_r(\omega)}{Cc_ph/k_t^3}$	Heat per Unit Volume of Blood Transported by Thermodynamic Processes / Energy per Unit Volume Associated with Elastic Storage in Vascular Tissue

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Viscous Compliance	$\bar{J}_1(\omega)$	$M^{-1}LT^2$	$\dfrac{\bar{J}_1(\omega)}{Cc_p h/k_t{}^3}$	Heat per Unit Volume of Blood Transported by Thermodynamic Processes Heat per Unit Volume Associated with Viscous Dissipation in Vascular Tissue
Complex Elastic Modulus:	$\bar{\mathscr{E}}$	$ML^{-1}T^{-2}$	$\dfrac{\bar{\mathscr{E}}}{k_t{}^3/Cc_p h}$	Energy per Unit Volume Associated with Elastic Storage and Viscous Dissipation in Vascular Tissue Heat per Unit Volume of Blood Transported by Thermodynamic Processes
Storage Modulus	$\bar{\mathscr{E}}_r(\omega)$	$ML^{-1}T^{-2}$	$\dfrac{\bar{\mathscr{E}}_r(\omega)}{k_t{}^3/Cc_p h}$	Energy per Unit Volume Associated with Elastic Storage in Vascular Tissue Heat per Unit Volume Transported by Blood Through Thermodynamic Processes
Viscous Modulus	$\bar{\mathscr{E}}_1(\omega)$	$ML^{-1}T^{-2}$	$\dfrac{\bar{\mathscr{E}}_1(\omega)}{k_t{}^3/Cc_p h}$	Heat per Unit Volume Associated with Viscous Dissipation in Vascular Tissue Heat per Unit Volume Dissipated by Thermodynamic Processes in Fluid

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Complex Impedance Function	$\overline{\mathscr{E}}_\mu$	$ML^{-1}T^{-2}$	$\dfrac{\overline{\mathscr{E}}_\mu}{k_t/c_p}$	Energy per Volumetric Flow Rate of Blood Associated with Elastic Storage and Viscous Dissipation in Vascular Tissue Heat per Volumetric Flow Rate of Blood Transported by Conduction
Complex Viscous Modulus	$\omega\overline{\mathscr{E}}_\mu$	$ML^{-1}T^{-2}$	$\dfrac{\omega\overline{\mathscr{E}}_\mu}{k_t{}^3/Cc_ph}$	Heat per Unit Volume Generated by Viscous Dissipation in Vascular Tissue Heat per Unit Volume Dissipated by Thermodynamic Effects in Fluid
Constant Stress in Vascular Wall	τ_0	$ML^{-1}T^{-2}$	$\dfrac{\tau_0}{k_t{}^3/Cc_ph}$	Energy per Unit Volume Associated with Constant Stress in Vascular Wall Energy per Unit Volume Associated with Thermal Properties of Fluid
Convection Conductance (Film) Coefficient	h_w	$MT^{-3}\theta^{-1}$	$\dfrac{h_w}{h}$	*

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Creep Compliance	$\mathcal{E}_c(t)$	$M^{-1}LT^2$	$\mathcal{E}_c(t)$	Heat per Unit Volume Transported by Blood Through Thermodynamic Processes
			$Cc_p h/k_t^3$	Elastic Energy per Unit Volume Associated with Creep Phenomenon in Vascular Tissue
Cross Sectional Area of Vascular Lumen	A	L^2	A	Cross Sectional Area of Vascular Lumen
			k_t^2/h^2	Reference Area Associated with Heat Transfer Processes
Derivative with Respect to Time of Vascular Wall Temperature	$\left(\frac{\partial T}{\partial t}\right)_w$	$T^{-1}\theta$	$\left(\frac{\partial T}{\partial t}\right)_w$	Rate of Change of Vascular Wall Temperature Over Time
			$k_t^8/C^3c_p h^5$	Rate of Change of Blood Temperature Over Time
Dynamic Modulus of Elasticity	$\mathcal{E}_D$	$ML^{-1}T^{-2}$	$\mathcal{E}_D$	Energy per Unit Volume Associated with Elastic Storage in Vascular Tissue
			$k_t^3/Cc_p h$	Heat per Unit Volume Transported by Blood Through Thermodynamic Processes

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Effective Diffusion Coefficient	D_e	L^2T^{-1}	$\dfrac{D_e}{k_t{}^4/Ch^3}$	Energy Transported per Mass Flow Rate of Blood by Diffusion Through Tortuous Pores Heat Transported per Mass Flow Rate of Blood by Thermodynamic Processes
Electrical Permeability	P_E	$M^{-1}L^{-1}Tq$	$\dfrac{P_E}{Ch^2F/k_t{}^3}$	Energy Transported by Mass Flux Due to Electromotive Diffusion Heat Transported by Mass Flux Through Electrothermodynamic Processes
Electrical Resistance	R^*	$ML^2T^{-1}q^{-2}$	$\dfrac{R^*}{c_pk_t{}^4/C^2h^3F^2}$	Resistance per Unit Length of Membrane to Current or Ionic Flow Resistance per Unit Length of Membrane to Heat Flow
Equilibrium Potential of Vascular Wall for Species S	$\mathscr{E}_S$	$ML^2T^{-2}q^{-1}$	$\dfrac{\mathscr{E}_S}{k_t{}^6/C^2h^4F}$	Voltage Applied Across Membrane to Prevent Electrochemical Diffusion Thermal Gradient Applied Across Membrane to Prevent Heat Transfer

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Extravascular Compression Pressure	p_{ev}	$ML^{-1}T^{-2}$	$\frac{p_{ev}}{k_t^3/Cc_p h}$	Energy per Unit Volume Associated with Pressure Energy (Potential) Due to Extravascular Compression Energy per Unit Volume Associated with Thermal Properties of Fluid
Firing Frequency of: Baroreceptors	$f_B{}^i$	T^{-1}	$\frac{f_B{}^i}{k_t^2/Ch}$	Time Scale Associated with Diffusion of Heat Through Blood Time Scale Associated with Firing Frequency of Baroreceptors
Chemoreceptors	f_{CM}	T^{-1}	$\frac{f_{CM}}{k_t^2/Ch}$	Time Scale Associated with Diffusion of Heat Through Blood Time Scale Associated with Firing Frequency of Chemoreceptors
Lung Inflation Receptors (Pulmonary Stretch Receptors)	f_{LUNG}	T^{-1}	$\frac{f_{LUNG}}{k_t^2/Ch}$	Time Scale Associated with Diffusion of Heat Through Blood Time Scale Associated with Firing Frequency of Pulmonary Strength Receptors

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Osmoreceptors	f_{OSM}	T^{-1}	$\frac{f_{OSM}}{k_t^2/Ch}$	Time Scale Associated with Diffusion of Heat Through Blood Time Scale Associated with Firing Frequency of Osmoreceptors
Stretch Receptors in Core Region	f_{SR}	T^{-1}	$\frac{f_{SR}}{k_t^2/Ch}$	Time Scale Associated with Diffusion of Heat Through Blood Time Scale Associated with Firing Frequency of Stretch Receptors in Core Region
Thermoreceptors (mucosal, hypothalamic, spinal cord, cutaneous, central visceral)	f_{THERM}	T^{-1}	$\frac{f_{THERM}}{k_t^2/Ch}$	Time Scale Associated with Diffusion of Heat Through Blood Time Scale Associated with Firing Frequency of Thermoreceptors
Generalized Static Young's Moduli	$\mathcal{E}_i$	$ML^{-1}T^{-2}$	$\frac{\mathcal{E}_i}{k_t^3/Cc_ph}$	Energy per Unit Volume Associated with Elastic Energy in Vascular Tissue Energy per Unit Volume Associated with Thermal Properties of Fluid

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Hydraulic Diameter of Blood Vessel	D^*	L	$\frac{D^*}{k_t/h}$	Hydraulic Diameter of Blood Vessel / Length Scale Associated with Heat Transfer Processes
Hydrostatic Pressure-Filtration Coefficient	P^*	$ML^{-2}T^{-2}$	$\frac{P^*}{k_t^2/Cc_p}$	Energy per Unit Fluid Volume per Unit Length of Membrane Associated with Pressure Energy Causing Hydrostatic Flow / Energy per Unit Fluid Volume per Unit Length of Blood Vessel Associated with Thermodynamic Properties of Fluid
Hysteresis of Vascular Wall Tissue	$\psi(t)$	$ML^{-1}T^{-2}$	$\frac{\psi(t)}{k_t^3/Cc_p h}$	Energy per Unit Volume Dissipated by Vascular Tissue Upon Cyclic Loading and Unloading / Heat per Unit Volume Transported by Blood Through Thermodynamic Processes
Internal Diameter of Blood Vessel	D	L	$\frac{D}{k_t/h}$	Internal Diameter of Blood Vessel / Length Scale Associated with Heat Transfer Processes

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Internal Radius of Blood Vessel	r_a	L	$\frac{r_a}{k_t/h}$	Internal Radius of Blood Vessel / Length Scale Associated with Heat Transfer Processes
Joule Coefficient	η_w	$MLT^{-2}\theta^{-1}$	$\frac{\eta_w}{Ch/k_t}$	Elastic Energy Associated with a Constant Length of Vascular Tissue at a Given Temperature / Heat Dissipated by Blood Through a Constant Length of Blood Vessel at a Given Temperature
Length of Blood Vessel	L	L	$\frac{L}{k_t/h}$	Length of Blood Vessel / Length Scale Associated with Heat Transfer Processes
Linear Thermal Expansion Coefficient	δ_w	T^{-1}	$\frac{\delta_w}{k_t^2/Ch}$	Time Scale Associated with Diffusion of Heat Through Blood / Time Scale Associated with Linear Thermal Expansion of Vascular Tissue

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Magnetic Permeability	p^*	MLq^{-2}	$\frac{p^*}{c_p k_t/ChF^2}$	Energy Transported by Mass Flux Due to Electromagnetic Diffusion Heat Transported by Mass Flux Through Electrothermodynamic Processes
Mass Density of Vascular Wall	ρ_w	ML^{-3}	$\frac{\rho_w}{Ch^3/c_p k_t^3}$	Energy per Degree Handled by the Vascular Wall Through Conduction and Convection Total Thermal Capacity of Blood
Maximum Stress in Vascular Wall	τ_{max}	$ML^{-1}T^{-2}$	$\frac{\tau_{max}}{k_t^3/Cc_p h}$	Heat per Unit Volume Associated with Maximum Stress in Vascular Wall Heat per Unit Volume Associated with Thermal Properties of Fluid
Mean Blood Velocity (Arterial) Velocity Profile of Blood	v $v(r)$	LT^{-1}	$\frac{v}{k_t^3/Ch^2}$	Mean Arterial Blood Velocity Rate at Which Heat Diffuses Through Blood

TABLE I (continued)

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Minimum Stress in Vascular Wall	τ_{min}	$ML^{-1}T^{-2}$	$\frac{\tau_{min}}{k_t^3/Cc_p h}$	Heat per Unit Volume Associated with Minimum Stress in Vascular Wall ——— Heat per Unit Volume Associated with Thermal Properties of Fluid
Mobility Constant	n^*	$M^{-1}T$	$\frac{n^*}{c_p h/k_t^2}$	Rate of Mass Flow Due to Thermodynamic Processes ——— Rate of Mass Flow Due to Electromotive Diffusion
Myogenic Activity of Vascular Smooth Muscle Tissue	f_{SM}	T^{-1}	$\frac{f_{SM}}{k_t^2/Ch}$	Time Scale Associated with Diffusion of Heat Through Blood ——— Time Scale Associated with Myogenic Activity of Vascular Smooth Muscle Tissue
Natural Frequency of Vascular Wall	ω_n	T^{-1}	$\frac{\omega_n}{k_t^2/Ch}$	Time Scale Associated with Diffusion of Heat Through Blood ——— Time Scale Associated with Kinematic Translation of Vascular Wall

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Osmotic Force/Volume for Species S	$\vec{\Omega}$	$ML^{-2}T^{-2}$	$\dfrac{\vec{\Omega}}{k_t^2/Cc_p}$	Osmotic Force per Unit Volume of Fluid for Species S Force per Unit Volume Associated with Thermal Properties of Fluid
Osmotic Permeability Coefficient	P_{H_2O}	LT^{-1}	$\dfrac{P_{H_2O}}{k_t^3/Ch^2}$	Rate at Which Mass is Transported by Osmosis Through Membranes Rate at Which Heat Diffuses Through Blood
Osmotic Pressure-Filtration Coefficient	P_0	L^2T^{-1}	$\dfrac{P_0}{k_t^4/Ch^3}$	Energy Transported per Mass Flow Rate of Blood by Osmosis Heat Transported per Mass Flow Rate of Blood by Thermodynamic Processes
Peak Flow Velocity (as measured at root of aorta)	v_{max}	LT^{-1}	$\dfrac{v_{max}}{k_t^3/Ch^2}$	Peak Flow Velocity at Root of Aorta Rate at Which Heat Diffuses Through Blood

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Perimeter of Blood Vesssel	P	L	$\frac{P}{k_t/h}$	Perimeter of Blood Vessel / Length Scale Associated with Heat Transfer Processes
Permeability Coefficient for Electromotive Diffusion	V_s	qT^{-1}	$\frac{V_s}{k_t^2F/c_ph}$	Rate at Which Charge is Transported Through Membrane by Electromotive Diffusion / Rate at Which Charge is Transported Through Blood by Electrothermodynamic Processes
Permeability Coefficient for Ordinary Diffusion	P_s	LT^{-1}	$\frac{P_s}{k_t^3/Ch^2}$	Rate at Which Mass is Transported by Ordinary Diffusion Through Membranes / Rate at Which Heat Diffuses Through Blood
Pore Diameter	d	L	$\frac{d}{k_t/h}$	Pore Diameter / Length Scale Associated with Heat Transfer Processes

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Pore Fluid Mass Density	ρ_p	ML^{-3}	$\frac{\rho_p}{Ch^3/c_p k_t^3}$	Energy per Degree Handled by Pore Fluid Through Conduction and Convection / Total Thermal Capacity of Blood
Pulmonary Artery Pressure	P_{pa}	$ML^{-1}T^{-2}$	$\frac{P_{pa}}{k_t^3/Cc_p h}$	Energy per Unit Volume Associated with Pressure Energy (Potential) in Pulmonary Artery / Energy per Unit Volume Associated with Thermal Properties of Fluid
Radius of Curvature (Axial)	R_v	L	$\frac{R_v}{k_t/h}$	Axial Radius of Curvature / Length Scale Associated with Heat Transfer Processes
Radius of Curvature (Cross Sectional)	R_x	L	$\frac{R_x}{k_t/h}$	Cross Sectional Radius of Curvature / Length Scale Associated with Heat Transfer Processes

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Relaxation Modulus for Vascular Wall	$\mathcal{E}_R(t)$	$ML^{-1}T^{-2}$	$\frac{\mathcal{E}_R(t)}{k_t^3/Cc_ph}$	Energy per Unit Volume Associated with Stress Relaxation of Vascular Wall / Energy per Unit Volume Associated with Thermal Properties of Fluid
Resonance Frequency of Vascular Wall (Driving)	ω_d	T^{-1}	$\frac{\omega_d}{k_t^2/Ch}$	Time Scale Associated with Diffusion of Heat Through Blood / Time Scale Associated with Kinematic Translation of Vascular Wall at Resonance
Size of Roughness Projections	ζ	L	$\frac{\zeta}{k_t/h}$	Size of Roughness Projections On Vascular Tissue / Length Scale Associated with Heat Transfer Processes
Specific Conductivity of Vascular Wall	$1/\rho^*$	$M^{-1}L^{-3}Tq^2$	$\frac{1/\rho^*}{C^2h^4F^2/c_pk_t^5}$	Affinity of Membrane to Current or Ionic Flow / Affinity of Membrane to Heat Transfer

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Specific Heat of Vascular Wall (Constant Pressure)	c_p^*	$L^2T^{-2}\theta^{-1}$	$\frac{c_p^*}{c_p}$	*
Specific Heat of Vascular Wall (Constant Volume)	c_v^*	$L^2T^{-2}\theta^{-1}$	$\frac{c_v^*}{c_p}$	Heat Required to Raise 1 gram of Vascular Tissue 1°C at Constant Volume Heat Required to Raise 1 gram of Blood 1°C at Constant Pressure
Specific Resistivity of Vascular Wall	ρ^*	$ML^3\ T^{-1}q^{-2}$	$\frac{\rho^*}{c_p k_t^5/C^2h^4F^2}$	Resistance of Membrane to Current or Ionic Flow Resistance of Membrane to Heat Flow
Specific Vascular Wall Conductance	g	$M^{-1}L^{-4}Tq^2$	$\frac{g}{C^2h^5F^2/c_p k_t^6}$	Affinity to Current or Ionic Flow per Unit Length of Membrane Affinity to Heat Transfer per Unit Length of Membrane Traversed by Blood

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Speed of Propagation (Phase Velocity) of Pulse Wave Through Vascular Wall	v_w	LT^{-1}	$\frac{v_w}{k_t^3/Ch^2}$	Rate at Which the Pulse Wave Moves Through the Vascular Wall ——— Rate at Which Heat Diffuses Through Blood
Strain Energy	$\psi_s(t)$	ML^2T^{-2}	$\frac{\psi_s(t)}{k_t^6/Cc_ph^4}$	Energy Associated with Strain in Vascular Wall ——— Energy Associated with Thermal Properties of Fluid
Strain Rate in Vascular Smooth Muscle	$\dot{\varepsilon}_{SM}$	T^{-1}	$\frac{\dot{\varepsilon}_{SM}}{k_t^2/Ch}$	Time Scale Associated with Diffusion of Heat Through Blood ——— Time Scale Associated with Strain Rate in Vascular Smooth Muscle
Strain Relaxation Time Constant (same as Strain Retardation Time Constant)	λ_F	T^{-1}	$\frac{\lambda_F}{k_t^2/Ch}$	Time Scale Associated with Diffusion of Heat Through Blood ——— Time Scale Associated with Strain Relaxation of Vascular Tissue

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Stress Relaxation Time Constant (same as Stress Retardation Time Constant)	λ_ε	T^{-1}	$\dfrac{\lambda_\varepsilon}{k_t^2/Ch}$	Time Scale Associated with Diffusion of Heat Through Blood / Time Scale Associated with Stress Relaxation of Vascular Tissue
Surface Diffusion Coefficient of Vascular Wall	D_K^*	L^2T^{-1}	$\dfrac{D_K^*}{k_t^4/Ch^3}$	Energy Transported per Mass Flow Rate of Blood by Surface Diffusion / Heat Transported per Mass Flow Rate of Blood by Thermodynamic Processes
Temperature of Vascular Smooth Muscle	T_m	θ	$\dfrac{T_m}{k_t^6/C^2c_ph^4}$	Temperature of Vascular Smooth Muscle / Reference Temperature Scale Associated with Heat Transfer Processes
Temperature of Vascular Wall (Inner)	T_{w_i}	θ	$\dfrac{T_{w_i}}{k_t^6/C^2c_ph^4}$	Inner Temperature of Vascular Wall / Reference Temperature Scale Associated with Heat Transfer Processes

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Temperature of Vascular Wall (Outer)	T_{w_o}	θ	$\frac{T_{w_o}}{k_t^6/C^2 c_p h^4}$	Outer Temperature of Vascular Wall / Reference Temperature Scale Associated with Heat Transfer Processes
Thermal Conductivity of Vascular Wall	k_w	$MLT^{-3}\theta^{-1}$	$\frac{k_w}{k_t}$	*
Thermal Diffusivity of Vascular Wall	α_w	L^2T^{-1}	$\frac{\alpha_w}{k_t^4/Ch^3}$	Time Rate of Change of Temperature in Vascular Wall / Time Rate of Change of Heat Influx or Efflux from Vascular Wall
Thickness of Vascular Wall	a	L	$\frac{a}{k_t/h}$	Thickness of Vascular Wall / Length Scale Associated with Heat Transfer Processes

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Time-Dependent Shearing Stress in Vascular Wall	$\tau^*(t)$	$ML^{-1}T^{-2}$	$\dfrac{\tau^*(t)}{k_t{}^3/Cc_ph}$	Heat per Unit Volume Associated with Shear Effects in Vascular Wall Over Time Heat per Unit Volume Dissipated Over Time by the Thermal Properties of Blood
Tissue Dashpot (Viscous) Constant	B_j $j=1,2...$	MT^{-1}	$\dfrac{B_j}{k_t{}^2/c_ph}$	Energy per Unit Area per Unit Time Associated with Viscous Dissipation During Vascular Tissue Deformation Heat per Unit Area per Unit Time Transported by Thermodynamic Processes in Blood
Tissue Elastic Constant	K_j $j=1,2...$	MT^{-2}	$\dfrac{K_j}{k_t{}^4/Cc_ph^2}$	Elastic Energy per Unit Area Associated with Vascular Tissue Deformation Heat per Unit Area Transported by Thermodynamic Processes in Blood
Total Surface Area of Vascular System (Heat and Mass Transfer)	A_v	L^2	$\dfrac{A_v}{k_t{}^2/h^2}$	Total Surface Area of Vascular System Available for Heat and Mass Transfer Reference Area Associated with Heat Transfer Processes

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Vascular Smooth Muscle Stress	τ_{sm}	$ML^{-1}T^{-2}$	$\frac{\tau_{sm}}{k_t^3/Cc_ph}$	Heat per Unit Volume Associated with Shear Effects in Vascular Smooth Muscle / Heat per Unit Volume Dissipated by the Thermal Properties of Blood
Velocity of Vascular Wall	v_w^*	LT^{-1}	$\frac{v_w^*}{k_t^3/Ch^2}$	Velocity of Vascular Wall / Rate at Which Heat Diffuses Through Blood
Venous Partial Pressure of CO_2	pCO_2	$ML^{-1}T^{-2}$	$\frac{pCO_2}{k_t^3/Cc_ph}$	Energy per Unit Volume Associated with Venous Partial Pressure of CO_2 / Heat per Unit Volume of Blood Transported by Thermodynamic Processes

TABLE 1 (continued)

D. MISCELLANEOUS

VARIABLE	SYMBOL	DIMENSIONS	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Basal Metabolic Rate	BMR	ML^2T^{-3}	$\frac{BMR}{k_t^8/C^2c_ph^5}$	Rate at Which Heat is Produced Due to Metabolism Rate at Which Heat is Dissipated Through Blood
Body Core Temperature	T_C	θ	$\frac{T_C}{k_t^6/C^2c_ph^4}$	Body Core Temperature Reference Temperature Scale Associated with Heat Transfer Processes
Breathing Rate	BR	T^{-1}	$\frac{BR}{k_t^2/Ch}$	Time Scale Associated with Diffusion of Heat Through Blood Time Scale Associated with Breathing Rate

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSION	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
CO_2 Ventilation Rate	$\dot{V}_{CO_2}$	L^3T^{-1}	$\dfrac{\dot{V}_{CO_2}}{k_t^5/Ch^4}$	Volume of CO_2 per Unit Time Released in Alveolar Air Space / Reference Volume of Blood per Unit Time Associated with Heat Transfer Processes
Energy of Hydration	$\mathscr{H}$	ML^2T^{-2}	$\dfrac{\mathscr{H}}{k_t^6/Cc_ph^4}$	Energy Associated with Chemical Hydration / Energy Associated with Thermal Properties of Blood
Environmental (Extravascular) Temperature	T_E	θ	$\dfrac{T_E}{k_t^6/C^2c_ph^4}$	Environmental (Extravascular) Temperature / Reference Temperature Scale Associated with Heat Transfer Processes
Extracellular Fluid Space (Volume)	ECF	L^3	$\dfrac{ECF}{k_t^3/h^3}$	Extracellular Fluid Volume / Reference Volume of Blood Associated with Heat Transfer Processes
Faraday Constant	F	*	*	*

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSION	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Heat Flow	q	ML^2T^{-3}	$\dfrac{q}{k_t^8/C^2c_ph^5}$	$\dfrac{\text{Rate of Overall Heat Transfer in Body}}{\text{Rate of Heat Transfer Through Blood by Thermodynamic Processes}}$
Heat Flow Due to Conduction	q_{COND}	ML^2T^{-3}	$\dfrac{q_{COND}}{k_t^8/C^2c_ph^5}$	$\dfrac{\text{Rate of Heat Transfer by Conduction}}{\text{Rate of Heat Transfer Through Blood by Other Thermodynamic Processes}}$
Heat Flow Due to Convection	q_{CONV}	ML^2T^{-3}	$\dfrac{q_{CONV}}{k_t^8/C^2c_ph^5}$	$\dfrac{\text{Rate of Heat Transfer by Convection}}{\text{Rate of Heat Transfer Through Blood by Other Thermodynamic Processes}}$
Intracellular Fluid Space (Volume)	ICF	L^3	$\dfrac{ICF}{k_t^3/h^3}$	$\dfrac{\text{Intracellular Fluid Volume}}{\text{Reference Volume of Blood Associated With Heat Transfer Processes}}$

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSION	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
O_2 Ventilation Rate	$\dot{V}_{O_2}$	L^3T^{-1}	$\dfrac{\dot{V}_{O_2}}{k_t^5/Ch^4}$	Volume of O_2 per Unit Time Extracted in Alveolar Air Space Reference Volume of Blood per Unit Time Associated with Heat Transfer Processes
Rate of Environmental Cooling (Ambient)	$\dfrac{dT_E}{dt}$	$T^{-1}\theta$	$\dfrac{\frac{dT_E}{dt}}{k_t^8/C^3c_ph^5}$	Change in Ambient Temperature Over Time Change in Body Temperature per Unit Time as a Result of Heat Transfer Processes
Sensitivity Coefficients for Baroreceptor Pressure Response	G_1	$M^{-1}LT^2$	$\dfrac{G_1}{Cc_ph/k_t^3}$	The Responsiveness of Baroreceptors to Changes in Arterial Pressure Over Time The Responsiveness of Thermoreceptors to Temperature Changes in Blood Over Time
	G_2	$M^{-1}LT^2$	$\dfrac{G_2}{Cc_ph/k_t^3}$	
	G_3	$M^{-1}LT$	$\dfrac{G_3}{c_p/k_t}$	

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSION	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Species Concentration in Extravascular Environment	$[S]_E$	ML^{-3}	$\dfrac{[S]_E}{Ch^3/c_p k_t^3}$	Energy per Degree Handled by the Fluid Through Conduction and Convection Associated with the Presence of Species in the Extravascular Environment
				Total Thermal Capacity of the Blood
Striated Skeletal Muscle Mass of Shivering Individual	m_W	M	$\dfrac{m_W}{C/c_p}$	Striated Skeletal Muscle Mass of Shivering Individual
				Mass Scale Associated with Heat Transfer Processes
Temperature Gradient Driving Heat In at Core	$\left(\frac{\partial T}{\partial r}\right)_C$	$L^{-1}\theta$	$\dfrac{\left(\frac{\partial T}{\partial r}\right)_C}{k_t^5/C^2 c_p h^3}$	Heat Transfer Into Body Core
				Heat Transfer Associated with Blood Flow
Temperature Gradient Driving Heat Out at Periphery	$\left(\frac{\partial T}{\partial r}\right)_E$	$L^{-1}\theta$	$\dfrac{\left(\frac{\partial T}{\partial r}\right)_E}{k_t^5/C^2 c_p h^3}$	Heat Transfer Out to Body Periphery
				Heat Transfer Associated with Blood Flow

TABLE 1 (continued)

VARIABLE	SYMBOL	DIMENSION	DERIVED DIMENSIONLESS PARAMETER	PHYSICAL SIGNIFICANCE
Universal Gas Constant	R	$L^2T^{-2}\theta^{-1}$	$\frac{R}{c_p}$	Heat Required to Raise 1 mole of Gas 1°K
				Heat Required to Raise 1 gram of Blood 1°C at Constant Pressure
Vapor Pressure	p_o	$ML^{-1}T^{-2}$	$\frac{p_o}{k_t{}^3Cc_ph}$	Energy per Unit Volume Associated with Vapor Pressure
Vapor Pressure Lowering	Δp_o			Heat per Unit Volume of Blood Transported By Thermodynamic Processes
Volumetric Urinary Output	Q_u	L^3T^{-1}	$\frac{Q_u}{k_t{}^5/Ch^4}$	Volume of Urine Produced per Unit Time
				Reference Volume of Blood per Unit Time Associated with Heat Transfer Processes

TABLE 2

DERIVED FUNDAMENTAL SCALES ASSOCIATED WITH ELECTROTHERMODYNAMIC EFFECTS

DIMENSION		SCALE	VALUE([17])
Mass	M	$\frac{C}{c_p}$	4.35 Kilograms
Length	L	$\frac{k_t}{h}$	2.75 Millimeters
Time	T	$\frac{Ch}{k_t^2}$	4.16 Months
Temperature	θ	$\frac{k_t^6}{C^2 c_p h^4}$	1.04×10^{-22} °C, or Nearly 0°C
Charge	q	$\frac{CF}{c_p}$	4.2 x 1[illegible] Coulombs

TABLE 3

OTHER DERIVED SCALES ASSOCIATED WITH ELECTROTHERMODYNAMIC EFFECTS

KINEMATIC QUANTITIES

Displacement (L):	k_t/h
Velocity (L/T):	k_t^3/Ch^2
Acceleration (L/T^2):	k_t^5/C^2h^3

KINETIC QUANTITIES

Angular Momentum ($\vec{r} \times m\vec{v}$) Angular Impulse ($\vec{r} \times \vec{F}T$)	k_t^4/c_ph^3
Force (F):	k_t^5/Cc_ph^3
Moment ($\vec{r} \times \vec{F}$):	k_t^6/Cc_ph^4
Momentum (Mv) Impulse (FT)	$k_t^3c_ph^2$
Power (FL/T):	$k_t^8/C^2c_ph^5$
Pressure or Stress (F/L^2):	k_t^3/Cc_ph
Work (FL) Energy (FL)	k_t^6/Cc_ph^4

THERMAL OR THERMODYNAMIC QUANTITIES

Heat Capacity (FL/θ):	k_t^6/Cc_ph^4
Temperature (θ):	$k_t^6/C^2c_ph^4$

TRANSPORT QUANTITIES

Diffusion (L^2/T):	k_t^4/Ch^3
Volumetric Flow Rate (L^3/T):	k_t^5/Ch^4

TABLE 4

LIST OF SYMBOLS USED IN TABLE 5

Bi =	Bingham Number =	$\tau_L/\mu_a v$ =	(Yield Stress)/(Viscous Stress)
Br =	Brinkman Number =	$\mu_a v^2/k_t \Delta\theta$ =	$\frac{\text{(Heat Produced by Viscous Dissipation)}}{\text{(Heat Transported by Molecular Conduction)}}$
C =	Total Thermal Capacity of Blood =	$\rho_f c_v V_B$	
D =	Diameter		
D' =	Molecular Diffusivity		
Ec =	Eckert Number =	$v^2/c_p \Delta\theta$ =	$\frac{\text{(Kinetic Energy)}}{\text{(Thermal Energy)}}$
Eu =	Euler Number =	$\Delta p/\rho_f v^2$ =	$\frac{\text{(Pressure Force)}}{\text{(Inertia Force)}}$
Fa_∞ =	"Modified" Fanning Number =	$2\tau_\infty/\rho_f v^2$ =	(Shear Stress)/(Dynamic Pressure)
Fo =	Fourier Number =	$k_t t/\rho_f c_p L^2$	
Ge =	Geometric Ratio =	ℓ/L	
K_Q =	Heat Transfer Number =	$q/v^3 L^2 \rho_f$	
L =	Length		

TABLE 4 (continued)

Le =	Lewis Number for Heat and Mass Transfer =	$D'\rho_f c_p/k_t$	
M =	Blood Mass Flux Rate =	$\rho_f V_B/At$	
Ms* =	Mass Flux of Species S		
Mt =	"Modified" Thompson (Mach) Number =	v/c	
Nu =	Nusselt Number =	hD/k_t	
Pe =	Peclet Number =	$\rho_f c_p vD/k_t$ =	(Pr)(Re) = $\frac{\text{(Heat Convection)}}{\text{(Heat Conduction)}}$
Pr =	Prandtl Number =	$c_p \mu_a/k_t$ =	$\frac{\text{(Hydrodynamic Boundary Layer Thickness)}}{\text{(Thermal Boundary Layer Thickness)}}$
PVR =	Prandtl Velocity Ratio =	$v/(\tau_w/\rho_f)^{1/2}$ =	(Inertia Force/Wall Shear Force)$^{1/2}$
Re =	Reynolds Number =	$\rho_f vD/\mu_a$ =	$\frac{\text{(Inertia Force)}}{\text{(Viscous Force)}}$
Sc =	Schmidt Number for Diffusion in Flow =	$\mu_a/\rho_f D'$	
Sn =	Stanton Number =	$h/c_p \rho_f v$ =	$\frac{\text{(Heat Transferred to Fluid)}}{\text{(Heat Transported by Fluid)}}$

TABLE 4 (continued)

St =	Strouhal Number =	fL/v =	$\frac{\text{(Frequency)}}{\text{(Translation Speed)}}$
W_E =	Work per Unit Mass Flux Due to Thermal Gradient		
W_T =	Work per Unit Mass Flux Due to Electromotive Gradient		
Z =	Valence Number of Ionic Species		
c =	Pulse Wave Speed		
τ_H =	Pulse Cycle		
ℓ =	Length Scale =	V_B/L^2	

TABLE 5

DERIVED DIMENSIONLESS PARAMETERS WRITTEN IN TERMS OF TRADITIONAL NON-DIMENSIONAL NUMBERS RELATED TO FLUID AND THERMODYNAMIC THEORY

DERIVED VARIABLE		CHARACTERISTIC SCALE	ASSOCIATED NON-DIMENSIONAL PARAMETER
Length: L		(k_t/h)	
Internal Diameter of Blood Vessel	D		(Nu)
Length of Blood Vessel	L		(Nu)(Ge)
Thickness of Vascular Wall	a		(Nu)(Ge)
Area: L^2		(k_t^2/h^2)	
Cross Sectional Area of Vascular Lumen	A		$(Nu)^2(Ge)$
Volume: L^3		(k_t^3/h^3)	
Quantity of Blood Pooling in Core	Q_B		$(Nu)^3(Ge)$
Velocity: LT^{-1}		(k_t^3/Ch^2)	
Velocity Profile of Blood	v(r)		$\frac{(Nu)^2(Pr)(Re)(Ge)}{\gamma}$

TABLE 5 (continued)

DERIVED VARIABLE	CHARACTERISTIC SCALE	ASSOCIATED NON-DIMENSIONAL PARAMETER
Myocardial Contraction Velocity u_m		$\frac{(Nu)^2(Pr)(Re)}{(\gamma)} \frac{(u_m)}{(v)} (Ge)$
Acceleration: LT^{-2}	(k_t^5/C^2h^3)	
Acceleration of Blood Leaving Ventricles a_B		$\frac{(Nu)^3(Pe)^2}{(\gamma)^2(Mt)^2} \frac{(A)}{(A_w)} (Ge)^2$
Temperature: θ	$(k_t^6/C^2c_ph^4)$	
Blood Temperature T_B		$\frac{(Nu)^4(Pr)^3(Re)^2}{(\gamma)^2(Br)} (Ge)^2$
Temperature of Vascular Smooth Muscle T_m		$\frac{(Nu)^4(Pr)^3(Re)^2}{(\gamma)^2(Br)} \frac{(\Delta T_m)}{(\Delta T_B)} (Ge)^2$
Temperature Gradient (Spatial): θL^{-1} (Inverse Linear Thermal Expansion Coefficient)	$(k_t^5/C^2c_ph^3)$	$\frac{(Nu)^5}{(Sn)^2(\gamma)^2(Ec)} (Ge)^2$

TABLE 5 (continued)

DERIVED VARIABLE	CHARACTERISTIC SCALE	ASSOCIATED NON-DIMENSIONAL PARAMETER
Temperature Gradient (Temporal): θT^{-1}	$(k_t{}^8/C^3c_ph^5)$	$\frac{(Nu)^8(St)}{(Sn)^3(\gamma)^3(Ec)}(Ge)^3$
Inverse Thermal Capacitance: $M^{-1}LT^2\theta$ $(1/\rho_f c_v)$	$(k_t{}^3/Ch^3)$	$(Nu)^3(Ge)$
Heat Flow: ML^2T^{-3} q	$(k_t{}^8/C^2c_ph^5)$	$\frac{(Nu)^5(Pe)^3(K_Q)}{(\gamma)^2}(Ge)$
Time: T	$(Ch/k_t{}^2)$	
Q-R-S Complex Interval t_{QRS}		$\frac{(\gamma)}{(Nu)(Pe)}\frac{(t_{QRS})}{(\tau_H)}$
Refractory Time of Cardiac Muscle t_r		$\frac{(\gamma)}{(Nu)(Pe)}\frac{(t_r)}{(\tau_H)}$

TABLE 5 (continued)

DERIVED VARIABLE	CHARACTERISTIC SCALE	ASSOCIATED NON-DIMENSIONAL PARAMETER
Frequency: T^{-1} (Strain Rate)	$(k_t{}^2/Ch)$	
Circular Frequency of Oscillating Blood Flow ω		$\frac{(St)(Nu)(Pe)}{\gamma}$ (Ge)
Natural Frequency of Vascular Wall ω_n		$\frac{(St)(Nu)(Pe)}{(\gamma)} \frac{(\omega_n)}{(\omega)}$ (Ge)
Strain Rate in Vascular Smooth Muscle $\dot{\varepsilon}_{SM}$		$\frac{(St)(Nu)(Pe)}{(\gamma)} \frac{(\dot{\varepsilon}_{SM})}{(\omega)}$ (Ge)
Mass: M	(C/c_p)	
Mass of Heart	m_H	$\frac{(\gamma)(m_H)}{(m_B)}$
Striated Skeletal Muscle Mass of Shivering Individual	m_W	$\frac{(\gamma)(m_W)}{(m_B)}$

TABLE 5 (continued)

DERIVED VARIABLE	CHARACTERISTIC SCALE	ASSOCIATED NON-DIMENSIONAL PARAMETER
Mass Density/Concentration: ML^{-3}	$(Ch^3/c_p k_t^3)$	
Mass Density of Blood ρ_f		$\frac{(Pe)(Sn)(\gamma)}{(Nu)^4} \frac{1}{(Ge)}$
Mass Density of Vascular Wall ρ_w		$\frac{(\gamma)}{(Nu)^3} \frac{(\rho)}{(\rho_f)} \frac{1}{(Ge)}$
Species Concentration in Blood $[S]_B$		$\frac{(\gamma)}{(Nu)^3} \frac{([S]_B)}{(\rho_f)} \frac{1}{(Ge)}$
Volumetric Flow Rate: L^3T^{-1}	(k_t^5/Ch^4)	
Coronary Perfusion Rate Q_c		$\frac{(Nu)^4}{(\gamma)(Fo)} (Ge)$

TABLE 5 (continued)

DERIVED VARIABLE	CHARACTERISTIC SCALE	ASSOCIATED NON-DIMENSIONAL PARAMETER
Stress, Pressure, and Moduli of Elasticity: $ML^{-1}T^{-2}$	$(k_t{}^3/Cc_p h)$	
Asymptotic Limiting Value of Thixotropic Fluid Shearing Stress Under Constant Load τ_∞		$\dfrac{(Fa_\infty)(Nu)(Pe)^2}{\gamma}$ (Ge)
Yield Stress τ_y		$\dfrac{(Nu)(Bi)(Pr)^2(Re)}{(\gamma)}$ (Ge)
Constant Stress in Vascular Wall τ_o		$\dfrac{(Nu)(Pe)^2}{(PVR)^2(\gamma)} \dfrac{(\tau_o)}{(\tau^*(t))}$ (Ge)
Vascular Smooth Muscle Stress τ_{sm}		$\dfrac{(Nu)(Pe)^2}{(PVR)^2(\gamma)} \dfrac{(\tau_{sm})}{(\tau^*(t))}$ (Ge)

TABLE 5 (continued)

DERIVED VARIABLE	CHARACTERISTIC SCALE	ASSOCIATED NON-DIMENSIONAL PARAMETER
Arterial Blood Pressure $p(t)$		$\frac{(Eu)(Nu)(Pe)^2}{(\gamma)}(Ge)$
Transport Coefficients: L^2T^{-1}	$(k_t{}^4/Ch^3)$	
Kinematic Viscosity ν_f		$\frac{(Nu)^4}{(Re)(Sn)(\gamma)}(Ge)$
Thermal Diffusivity α		$(Nu)^3(Ge)$
Thermal Diffusivity of Vascular Wall α_w		$(Nu)^3\frac{(k_w)}{(k_t)}\frac{(\rho_f)}{(\rho_w)}\frac{(c_v)}{(c_v{}^*)}(Ge)$
Dynamic Viscosity: $ML^{-1}T^{-1}$ μ_a	(k_t/c_p)	(Pr)

TABLE 5 (continued)

DERIVED VARIABLE	CHARACTERISTIC SCALE	ASSOCIATED NON-DIMENSIONAL PARAMETER
Electromotive Diffusion Coefficient: $L^{-3}Tq$ D_s^*	$(C^2h^4F/c_pk_t^5)$	$\frac{(Pr)(Z)}{(Nu)^4}\frac{(Le)^2}{(S_c)^2}\frac{(M_s^*)}{(M)}\frac{(W_T)}{(W_E)}$
Permeability Coefficient for Electromotive Diffusion: qT^{-1} V_s	(k_t^2F/c_ph)	$(Nu)^2\,(Re)\,\frac{(S_c)}{(Le)}\frac{(\rho_f)}{([S])}\frac{(M_s^*)}{(M)}\,(Ge)$
Electrical Resistance: $ML^2T^{-1}q^{-2}$ R^*	$(k_t^4c_p/C^2h^3F^2)$	$\frac{(Nu)^3}{(Pr)(Z)^2}\frac{(S_c)^2}{(Le)^2}\frac{(M)}{(M_s^*)}\frac{(W_E)}{(W_T)}$
Specific Vascular Wall Conductance: $M^{-1}L^{-4}Tq^2$ g	$(C^2h^5F^2/k_t^6c_p)$	$\frac{(Pr)(Z)(Le)^2}{(Nu)^5(S_c)^2}\frac{(M_s^*)}{(M)}\frac{(W_T)}{(W_E)}$

TABLE 6

LIST OF VARIABLES WHICH ARE ALREADY

DIMENSIONLESS BY DEFINITION

DIMENSIONLESS VARIABLE	SYMBOL
Blood	
Arrangement Factor	i
Dielectric Constant for Blood	κ
Emissivity of Blood	ϵ
Hematocrit (%)	H
Non-Newtonian Index	n
Percent O_2 Saturation (Hemoglobin)	% O_2
pH	pH
Species - Specific Constants for Rheologic Equation for Blood	C_1, C_2, C_3, C_4
Specific Heat Ratio for Blood	γ
Heart	
Efficiency of Cardiac Cycle (Overall)	η_t
Efficiency of Cardiac Muscle Contraction	η_m
Efficiency of Energy Conversion from Stroke Power to Fluid Kinetic Energy	η_k
Efficiency of Energy Conversion into Stroke Volume	η_s

TABLE 6 (continued)

DIMENSIONLESS VARIABLE	SYMBOL
Efficiency of the Heart	η_h
"Other" Efficiencies in Cardiac Cycle	η_n
Frequency Component of ECG Spectrum	n_i
Korotkoff Heart Sounds	$(db)_1$, $(db)_2$, $(db)_3$ $(db)_4$
"Other" Heart Sounds	$(db)_i$
Phase Lead Angle for Oscillating Blood Flow	ϕ_f
Magnitude of ϕ_f	$\|\phi_f\|$
Probability Density Function	$p(X)$
Probability Distribution Function	$P(X)$
Probability Range Function $\int p(X)dX$	
Vascular System	
Amplitude Magnification Factor (for cyclic loading of vascular wall)	Q
Branching Angles of Vascular Geometry	θ
Coefficient of Friction (Wall Pore and Pore Fluid)	s_f
Coefficient of Friction (Pore Fluid and Solute)	s_p
Coefficient of Friction (Wall Pore and Solute)	s_s
Constant Strain in Vascular Wall	ξ_0
Dielectric Constant for Vascular Wall	κ^*
Elastic After-Effect (Strain)	$\xi^*(t)$
Emissivity of Vascular Wall	ϵ_w
Form Factor	m

TABLE 6 (continued)

DIMENSIONLESS VARIABLE	SYMBOL
Fraction of Vascular Area Available for Heat Transfer to Body Core	A_c
Fraction of Vascular Area Available for Heat Transfer to Environment (near skin surface)	A_e
Friction Factor	f_R
Generalized Poisson Ratios for Vascular Smooth Muscle	σ_i $i = 0, 1, \ldots N$
Maximum Strain in Vascular Wall	ξ_{max}
Minimum Strain in Vascular Wall	ξ_{min}
Number of Anastomoses Open at any Time	N_2
Number of Collateral Pathways at any Time	N_3
Number of Patent Blood Vessels at any Time	N_1
Number of Pores/Membrane Area	c
Percent by Weight:	
Collagen	W_c
Elastin	W_e
Smooth Muscle Tissue	W_s
Phase Angle for Viscoelastic Blood Vessel Wall	ϕ_w
Magnitude of ϕ_w	$\|\phi_w\|$
Pore - Free Surface Area (% of A_v)	A_o
Porous Surface Area (% of A_v)	A_p
Reflection Coefficient (Staverman Factor)	b
Roughness Factor	ζ/D

TABLE 6 (continued)

DIMENSIONLESS VARIABLE	SYMBOL
Specific Heat Ratio at Vascular Wall	γ^*
	$i = 0, 1, \ldots, N$
Stimulation Coefficients for Vascular Smooth Muscle	q_i
Time-Dependent Strain in Vascular Wall	$\xi(t)$
Tortuosity Factor for Pores	δ^*
Total Number of Cycles (required for hysteresis to reach steady-state)	M
Vascular Smooth Muscle Strain	$\xi_m(\xi_m{}^2,$
	$\xi_m{}^3, \ldots)$
Volume Fraction of Water in Pores	ϕ_p
Miscellaneous	
"Activity Factor"	β
Ambient Humidity Ratio (%)	HR
Degree of Nonlinearity for any Model	N
Dissociation Constant for Electrolytes	D_i
e = 2.718	e
Ionic Valence of Species S	Z
Partition Coefficient	$\mathscr{P}_v$
Pi - 3.14159 (circumference/diameter)	π
Respiration Quotient	R_Q
Solubility	$\mathscr{S}$
Solubility Coefficient	$\mathscr{S}'$

TABLE 7

OTHER VARIABLES THAT CAN BE ASSOCIATED WITH CARDIOVASCULAR FUNCTION AND THERMOREGULATION

<u>Characteristics of Individual</u>	
Age	Yr
Anthropometric Build	
Height	Ht
Muscle Mass	
Physical Condition	
Cardiovascular System	
Central/Sympathetic Nervous System	
Endocrine System	
Musculoskeletal System (exercise)	
Weight	Wt
<u>Climate</u>	
Season of the Year (Fall, Winter, Spring, Summer)	
Relative Humidity	
Amount of Daylight	
Presence or Absence of Wind (Wind Velocity)	$\vec{U}$
Ambient Temperature	T_A
Time of Exposure	t_e
<u>Clothing</u>	
Amount	

TABLE 7 (continued)

Type

Thermal Properties

<u>Concentration and Properties of Carrier Molecules in Blood</u>

Affinity for Substrate (Stereospecificity)

Deformability

Degree of Hydration

Degree of Saturation

Geometry (Stereochemistry)

Mobility

<u>Diet of Individual</u>

Chemical Composition of Blood

Alcohol Consumption

Quantity and Type of Food Intake (especially fats and carbohydrates)

<u>History</u>

Family History

Predilection to Cold Stress

Frequency of Previous Exposure

Time Between Exposures

<u>Myocardial Muscle</u>

"Contractility"

TABLE 7 (continued)

Statistical Parameters

General Wave Shape of ECG

Kurtosis (Flatness Factor)

Skewness

Width Factor

Vascular System

Cold Induced Vaso-Dilatation	CIVD
Geometry of Vascular Wall	
Branches/Bifurcations	
Convergence/Divergence	
Curvature	
Parallelism/Taper	
Geometry of Vascular Smooth Muscle	
Length of Blood Vessels	
Development of Flow (inlet length)	
Effective Length of Pressure Drop	
End Effects	
Pulse Wave Reflection	
Orientation and Distribution of Blood Vessels	
Arterio-Venous Anastomoses	AVAs
Pores	
Cross Sectional Area	
Cross Sectional Contour	
Degree of Patency	

TABLE 7 (continued)

Length	
Mean Diameter	
Number	
Properties of Material Within Pore	
Smoothness	
Spatial Orientation	
Symmetry	
Wall Configuration	
Symmetry of Vascular Cross Section	
Vasoconstriction	
Arteries	
Capillaries	
Veins	
Vascular Lumen Patency	
Degree of Extravascular Compression	
Degree of Internal Occlusion	
Level of Smooth Muscle Tone	
Vascular Tone	
Venous Shunt Response	VSR
Atrio-Ventricular Countercurrent Heat Exchange (see N_1, N_2, N_3)	

TABLE 8

ENZYMES

Dehydrogenases:

glucose-6-α-hydroxybutyric dehydrogenase	HBD
glutamic dehydrogenase	GDH
isocitric dehydrogenase	ICD
lactic dehydrogenase	LDH
maleic dehydrogenase	MDH

Transaminases:

glutamic oxaloacetic transaminase	GOT (SGOT)*
glutamic pyruvic transaminase *(S = serum)	SGPT*

acid phosphatase	
aldolase	
alkaline phosphatase	
amino peptidase	
amylase	
arachidonic acid (test for presence of enzymes)	
aromatic L-amino acid decarboxylase	
cholinesterase	
creatinine phosphokinase	CPK (-MM, -MB, -BB)
dopamine-beta-hydroxylase	
guanase	
kinase I	
kinase II (precursor- kininogen)	

TABLE 8 (continued)

kininase	
lipase	LPP
ornithine carbamyl transferase	OCT
phenylethanolamine-N-methyltransferase	
prostacyclin	
renin	
tyrosine hydroxylase	

TABLE 9

HORMONES

Catecholamines (Blood and Vascular Smooth Muscle Tissue):	
epinephrine (adrenalin)	
norepinephrine (noradrenalin) (precursor- dopamine)	
local myocardial catecholamines	
Steroids:	
aldosterone	
corticosterones	"A", "B", or "S"
cortisone	
deoxycorticosterone	
hydroxycortisone (cortisol)	
acetylcholine	Ach
adrenocorticotropic hormone	ACTH
angiotensin I and II	
antidiuretic hormone (vasopressin)	ADH
calcitonin	
central nervous system chemical releasing factors	
corticotrophin releasing factor	CRF
dopa	
glucagon	
growth hormone release inhibiting hormone (somatostatin)	GHRIH
growth hormone releasing factor	GHRF
histamine	

TABLE 9 (continued)

insulin	
kinins:	
bradykinin	
kallikrein	
kallidin (lysin bradykinin)	
parathormone	
prostaglandins	D_2, E_2, F_2
serotonin	
somatotrophin (growth hormone)	GH
thyrocalcitonin	
thyrotrophin	TSH
thyrotrophin releasing hormone	TRH
thyroxin	
triiodothyronine	

TABLE 10

NUTRIENTS

water	H_2O
Amino Acids:	
tyrosine	
tryptophan	
Proteins:	
total protein concentration	[P]
albumins	[A]
total protein minus albumin	[TPMA]
fibrinogen	[F]
globulins:	[G]
α ceruloplasmin	(α_1, α_2, β, γ)
immunoglobulins	IgA, IgG, IgM
vascular wall:	
elastin	[E]
collagen	[C]
Carbohydrates:	
glucose	
mucopolysaccharide in vascular wall	[M]
Lipids and Fatty Acids:	

TABLE 10 (continued)

cholesterol (fats): (vitamin F)	
free	
esterified	
total	
triglycerides	
phospholipids	
total lipids	
subcutaneous fat content (insulation)	[fat]
effective insulation thickness of human body	I_T

TABLE 11

VITAMINS

A	retinol
B complex:	
B_1	thiamine
B_2	riboflavin (component- biotin)
B_3	niacin/nicotinamide
B_4	adenine
B_5	pantothenic acid
B_6	pyridoxine
B_{12}	
	choline folic acid inositol para-amino benzoic acid PABA
C	ascorbic acid
C complex	
	acerola hesperidin rutin
D	calciferol
E	tocopherol α-, β-
E complex	
K	(clotting)

TABLE 12

BUFFERING IONS

ammonium	NH_4^+
bicarbonate	HCO_3^-
hydrogen (pH)	H^+
phosphate	PO_4^{-3}
sulfate	SO_4^{-2}

MINERALS AND ELECTROLYTES

calcium	Ca
chloride	Cl
copper	Cu
iron	Fe
magnesium	Mg
phosphorus	P
potassium	K
sodium	Na

TRACE ELEMENTS

cadmium	Cd
chromium	Cr
cobalt	Cb
fluorine	F
iodine	I

TABLE 12 (continued)

protein-bound iodine	PBI
lithium	Li
manganese	Mn
molybdenum	Mo
selenium	Se
sulfur	S
zinc	Zn

BLOOD GASES

carbon dioxide	CO_2
oxygen	O_2
arterio-venous oxygen concentration difference	$\Delta[O_2]$
hemoglobin (percent saturated)	Hb

BYPRODUCTS OF METABOLISM

bilirubin	
blood urea nitrogen	BUN
carbon dioxide	CO_2
creatine	
creatinine	
lactic acid	
water	